Instruments for Amateur Radio Astronomy

Using RAL10KIT and RAL10AP to build a microwave radio telescope

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1. Introduction

The sky can be observed in many ways: the show is always magnificent and exciting. The sight of the starry vault on a clear winter night away from city lights is astonishing, even more wonderful when observing the details of the moon with binoculars or the planets with a telescope. These instruments, which amplify our visual capabilities, are well known to us: who has never had the pleasure of observing through a telescope during and educational evening offered by the local group of amateur astronomers? However, not everyone knows that there are other ways to look at the sky, and they are just as fascinating as the visual one.

We live submerged in a sea of electromagnetic waves generated by technology (mobile phones, Wi-Fi devices, television repeaters) and by the natural world, with radiations that also come from extra-terrestrial space. Planets, stars and the most distant galaxies emit electromagnetic waves: from gamma rays, X-rays, ultraviolet and visible radiation, up to infrared and radio emissions. The human eye detects the emissions in the visible band because mother nature has equipped us with the sense of sight, essential for our survival. To observe other "windows" of the electromagnetic spectrum, different instruments are needed, each one specialized to measure radiation in a certain frequency band.

It is possible to build a small radio telescope to study celestial objects in a different way, mastering the basic principles of this fascinating observation technique, in broad daylight and with cloudy skies. Undoubtedly, it is not trivial to pick up the radio emission of a distant galaxy: the signals are very weak, dimmed by artificial interference and background noise. To be successful you need knowledge of the subject, passion and operational continuity. Isn't this true of any business?

RadioAstroLab s.r.l. was the first Italian company to offer the market, in the year 2000, the RAL10 receiver, together with the information needed to build and use an amateur radio telescope. This instrument, cheap and designed to take advantage of commercial modules for satellite TV reception, has initiated many enthusiasts into radio astronomy.

Fig. 1: Radiometric module *RAL10KIT*.

Fig. 2: *RAL10AP* receiver.

Students, amateur astronomers, radio amateurs, schools and universities have built their own small radio telescopes to start exploring the "radio-sky". We have received appreciation and new requests, provided answers and supported enthusiasts by organizing events and conferences in many cities. We are happy and proud to have contributed to the development of amateur radio astronomy.

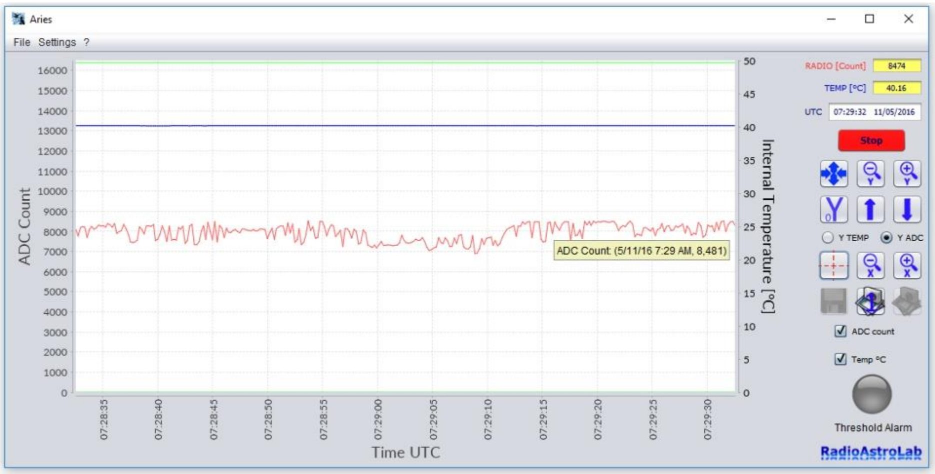


Fig. 3: The *ARIES* control and acquisition software, supplied with every *RAL10* receiver.

Today a new family of products is available in order to satisfy every enthusiast’s request and allows everyone to learn about radioastronomy by building, installing and using a small radio-telescope.

An experimental approach is always preferable: recording the radio waves originating from celestial objects with a "home-made" instrument is a very exciting experience. Of course, we cannot expect the performance of radio telescopes used in research, large and complex beyond comparison. However, the creation and implementation of an instrument built with one's own hands ensures a great deal of satisfaction and great educational value, making this a viable and educationally very interesting solution: many examples that are available online describe the construction of simple and cheap radio telescopes by using components and modules from the satellite TV market. These are interesting solutions that can be implemented immediately which, in any case, require practice and experience with the assembly of electronic circuits and, above all, with their development. On the other hand, if we want to start and be guaranteed of success, it will be preferable to move towards applications designed "ad hoc" for amateur radio astronomy, while not renouncing simplicity of use.

For these reasons, our offer includes the *RAL10KIT* module (Fig. 1) and the *RAL10AP* receiver (Fig. 2). These instruments, combined with easily available components, become a complete radio astronomy receiver which includes the interface for communication with a personal computer (PC) and the *ARIES* management software (Fig. 3). Building and learning how to use a radio telescope is both educationally very interesting and a simple and immediate approach to radio astronomy and basic instrumental techniques.

RAL10KIT has been designed for those who love to build receivers and have a minimum know-how of electronic assembly: the module must be assembled inside a suitable container equipped with power supply.

RAL10AP is a ready-to-use receiver, enclosed in an elegant and compact anodized aluminium container complete with external power supply.

The present paper's proposal includes the construction of an interesting amateur microwave radio telescope (10-12 GHz band) by using these devices. It is possible to complete the instrument by adding a few modules coming from the satellite TV market and following the instructions provided: antenna with external unit (low noise amplifier-frequency converter LNB - Low Noise Block) which includes the illuminator, the coaxial cable and the personal computer for data collection. For these devices there is a wide freedom of choice, given that *RAL10KIT* and *RAL10AP* are compatible with any product designed for satellite reception in the 10-12 GHz band, components available everywhere at low cost thanks to the widespread diffusion of this service. By using a parabolic reflector antenna with LNB complete with illuminator and by connecting the system to our receivers, we have created a microwave radiometer which is suitable for studying the thermal radiation of the Sun, the Moon and the most intense radio sources, with sensitivity depending on antenna size.

The construction and tuning of this instrument could be approached with satisfaction by students, radio amateurs and radio astronomy enthusiasts, that can obtain interesting results especially if using a larger antenna. Given the small wavelength, it is relatively simple to build instruments with good directive characteristics and a high-resolution. Even if particularly intense radio sources do not "shine" in this range of frequencies (excluding the Sun and the Moon), the sensitivity of the system can be enhanced by using the many available bandwidths and by reducing the influence of artificial disturbances: in an urban area the radio telescope can be easily installed on a roof or back-yard. The geostationary television satellites which can create interference are in a static and known location in the sky and it is not difficult to avoid them without limiting the observable field too much.

2. Radioastronomy and radio telescopes

Radio astronomy studies the sky by analysing the natural radio waves emitted by celestial bodies: any object radiates measurable electromagnetic waves which, picked up and displayed by the antenna, show the incoherent characteristics of broad-spectrum electrical noise.

In general, a *radio source* indicates any natural emitter of radio waves: in common use this term has become a synonym of cosmic radio sources. *Radio telescopes*, instruments that record the weak radio flux coming from extra-terrestrial space, include an antenna system, transmission lines and a receiver: the electronics amplify the signal picked up by the antenna making it measurable. Ultimately, devices for processing and recording information, as well as organs for controlling the instrument and for orienting the antenna, come into play (Fig. 4).

In honour of K. Jansky, the founder of radio astronomy, the measurement unit of the flux density of radio sources has been defined:

$$1\,Jy = 10^{-26}\,\frac{W}{m^2 \cdot Hz}$$

From this expression we can see how a radio telescope measures a radiant power coming from the sky which affects the surface of the antenna uptake, within the bandwidth of the receiver.

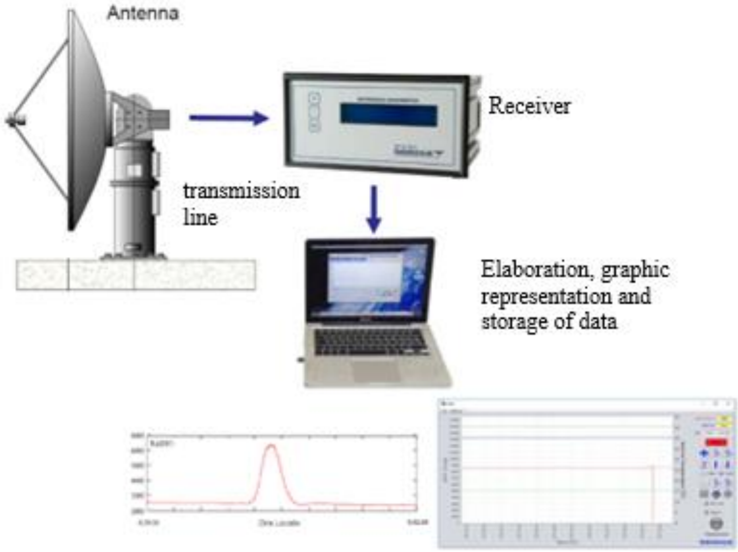


Fig. 4: Principal diagram of a simple microwave radio telescope.

An alternative way to express the power of the radiation "collected" by the antenna is through the concept of *brightness temperature*. If we direct the antenna of the instrument in a given area of the sky, particularly towards a radio source, we measure an increase in the intensity of the received signal which is proportional to the *brightness temperature* of that object, which will coincide with its physical temperature only if this is a *black body*, i.e., a material which (ideally) perfectly absorbs all the radiation that it receives, without reflecting it. In nature black bodies do not exist, but there are objects that approximate their behaviour very well within a limited frequency band. Therefore, a radio telescope could be defined as a sky thermometer: the measured temperature, i.e., the brightness temperature, will be proportional to the physical temperature of the region observed by the antenna thanks to a coefficient called *emissivity*, which quantifies the ability of the source to radiate energy, depending on its chemical-physical characteristics and frequency. The *emissivity* of a black body is equal to 1, with a brightness temperature coinciding with the physical temperature, whereas the *emissivity* of a material body (called *grey body*) is between 0 and 1, with a brightness temperature lower than the its physical temperature.

The basic diagram of a simple radio telescope is similar to that of a home radio-receiving device (such as, for example, a television, a car radio or a mobile phone): obviously the system is specialized and the performances are optimized for measuring space's very faint signals. In radio astronomy it is necessary (and difficult) to highlight the noise produced by the radio sources (useful signal) as opposed to the one generated by the electronics of the instrument and by the environment (unwanted signal), which is generally very intense: these background disturbances, electrically similar to those we hear when no station is tuned into a radio, they are identical in nature and are, in principle, indistinguishable.

3. The earth's atmosphere

The official classification of the radio spectrum frequency bands is shown in Fig. 5.

ITU DESIGNATION

Band	Frequency	wavelength
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

Fig. 5: Radio spectrum classification in frequency bands.

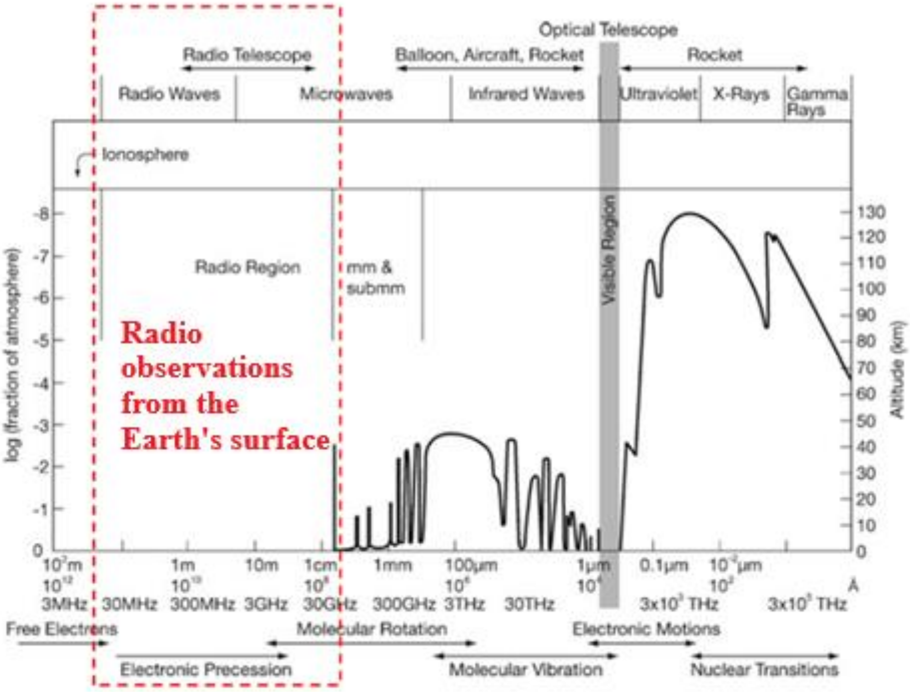


Fig. 6: Representation of the electromagnetic spectrum where the “radio window” has been highlighted.

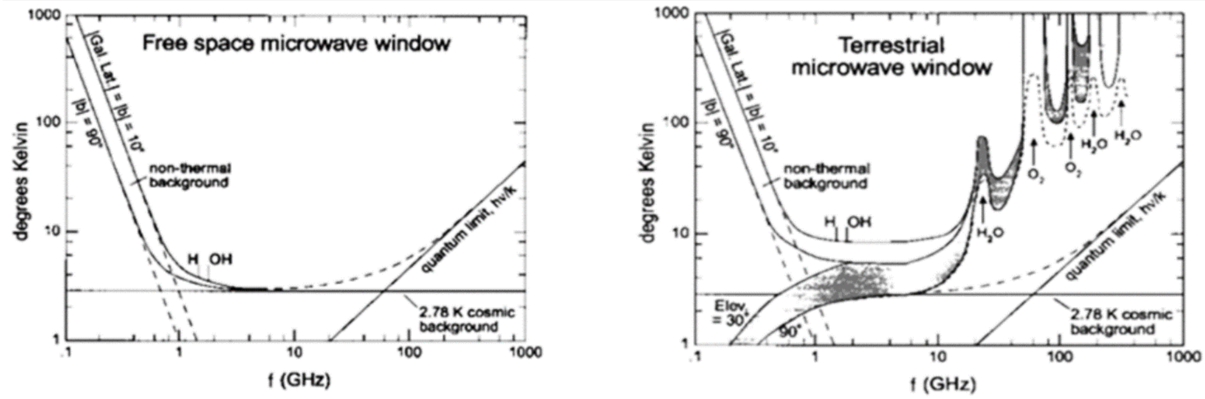


Fig. 7: Effects of the Earth's atmosphere, clearly visible by comparing the graphs representing the "radio window" of the electromagnetic spectrum seen from the ground and seen from a radio telescope operating in space.

Our atmosphere limits the frequencies that can be used for radio astronomy observations from the Earth's surface, since it acts as a filter for electromagnetic radiation from space. The direct measurement of cosmic radiation, in fact, is limited to two "windows" of the electromagnetic spectrum: the one between approximately 0.3 and 0.8 micrometres (visible band) and the one between approximately 1 centimetre and 1 meter of wavelength (radio band). The "radio window" is, in turn, limited in its lower threshold by the shielding effects of the ionosphere (electrically charged particles that act as a reflector for radio waves), and in its upper threshold by the phenomena of molecular absorption caused by water vapor and oxygen (Fig. 6, Fig. 7, Fig. 10). For these reasons (Fig. 7), the range of radio frequencies useful for radio astronomical ground-based observations is between approximately 20 MHz and 20 GHz.

4. Amateur radioastronomy

Admiring the technology and the size of professional radio telescopes, not to mention their "skyrocketing" costs, question rise as to whether an amateur radio astronomy activity is conceivable and, if so, what are the real possibilities of experimentation open to amateurs. Many of the experts of the visible sky, such as amateur astronomers, have fragmentary information on radio astronomy techniques and can only dream about the great instruments of research. It is widely believed that radio astronomy is essentially a discipline that is inaccessible to amateurs, due to limited possibilities for experimentation at an amateur level, therefore not very interesting for expanding one's knowledge of the sky. Clearly this is not the case, because there is an interesting and fascinating world to discover.

To overcome these obstacles, it is important to start from the basics, starting from concrete, economic and easily feasible projects, with safe and repeatable performances, accepting the limits achievable in an amateur activity. It is always recommended to start from simple and immediately successful projects, in order to gradually gain confidence with the instrumental techniques and the practice of radio astronomy observation, which are by no means to be taken for granted. It takes willingness to invest time and patience; a gradual approach to a discipline that is certainly less immediate and spectacular than observing the sky in its visible range, given that the human eye cannot pick up radio waves. In this field, visualizing the cosmic landscape and extracting the resulting information is not immediate: specific instruments (radio telescopes) are needed to detect radio signals and visualize them.

There are also problems concerning the equipment: do you need to be an electronic expert to make everything at home? Not necessarily.

Those with practical knowledge of electronics clearly have an advantage: there are excellent online examples that describe how to assemble a small radio telescope. However, to make the approach to radio astronomy easier for any person of good will, we propose the construction of a microwave radio telescope based on a modular philosophy in favour of simplicity, affordability and the reuse of parts for future expansions and developments. Anyone can build a radio telescope to explore the fascinating world of amateur radio astronomy.

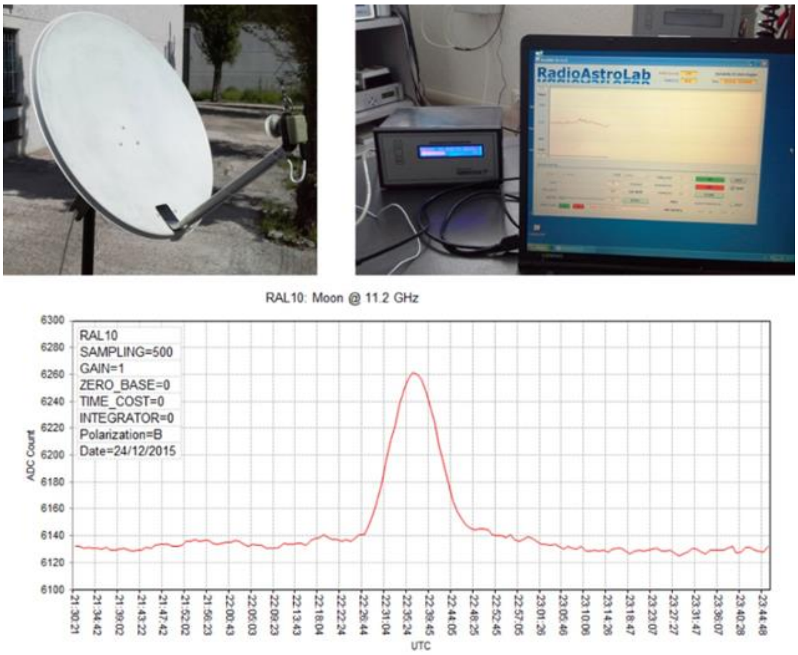


Fig. 8: Observing the lunar transit with a receiver-based radio telescope *RAL10*.

The simplest radio astronomy observation consists in measuring how the received signal intensity varies during the transit of a radio source (such as, for example, the Sun or the Moon) in the “field of view” of the antenna (transit recording). The radio telescope is pointed to the area of the sky where the passage of the radio source is expected, in its predicted motion, along with the formation of the classic bell-shaped trace displayed by the acquisition software (Fig. 8). The next step, more complex and time-consuming, involves recording the intensity of the signal received from different sections of the sky. By patiently and methodically collecting a series of measurements, a radio map of the observed region of the sky is drawn up. Obviously, observations are possible by “chasing” radio sources as for example when you want to monitor solar activity. This requires motorized and automatic equipment to manage the antenna’s orientation system.

Why start with just a microwave tool?

Being the collector of cosmic radiation, the antenna is the most important component of a radio telescope: the sensitivity and performance of the instrument will mainly depend on its size (let us overlook, for a moment, affordability, space and installation problems). Once the sensitivity and resolving power requirements for the radio telescope have been established, the dimensions required for the antenna increase considerably as the operating frequency decreases. This aspect is sufficient to create an infinite number of doubts and problems for those who intend to start an amateur radio astronomy activity.

Some of the questions we can ask ourselves are:

- In what frequency band is it best to operate in?
- Which radio sources can be observed through a small radio telescope?

- Are there any particular requirements to choose the instrument's installation site?

These questions are all linked.

The mechanisms that explain the emissions of radio sources are complex, linked to their chemical-physical characteristics. A good starting point is to label the most intense radio objects in the sky and find out how their emission varies depending on frequency (spectra of radio sources). Taking into account the sensitivity limits of amateur instruments, mainly due to the reduced antenna surface, the obvious choice is to favour the frequencies where radio sources are more intense and abundant. As shown in the Fig. 9 graph, apart from the fact that the Sun and the Moon roughly behave like black bodies in the radio band (at least as regards the emission of the quiet Sun), the other radio sources radiate with greater intensity for frequencies lower than 1 GHz, with a (non-thermal) mechanism that increases the intensity of the emission as the frequency decreases.

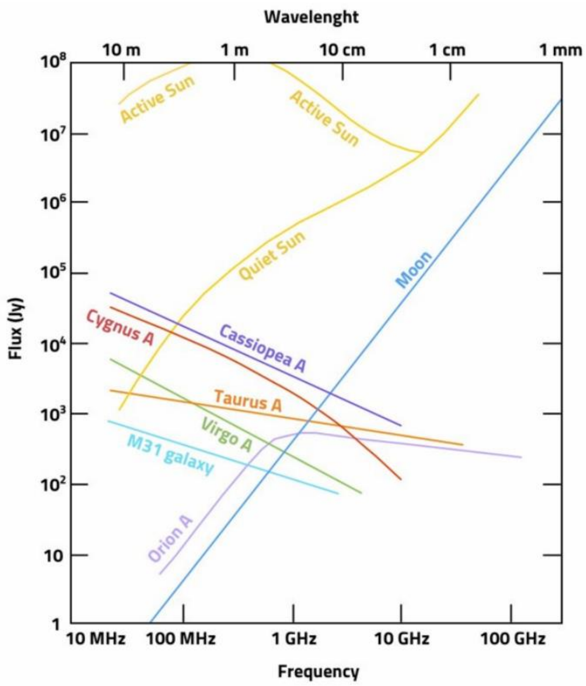


Fig. 9: Spectrum of the main radio sources.

However, it is necessary to consider a congestion of radio signals in the area where we will install the radio telescope, due to the presence of various interferences. Artificial disturbances, very intense in urban and industrialized areas, are the main obstacle for radio astronomy observation, as the radio spectrum becomes practically saturated. The most common natural sources of interference are lightning, atmospheric electrical discharges, radio emissions produced by charged particles in the upper part of the atmosphere (ionospheric disturbances), emissions from atmospheric gases and meteorological precipitations. Artificial interference is caused by disturbances originating from the distribution, use and transformation of electrical power, radar transmissions for military and civil air traffic control, terrestrial transmitting stations used for radio and television broadcasting services, transmitters and transponders on artificial satellites, cellular telephone network and military stations.

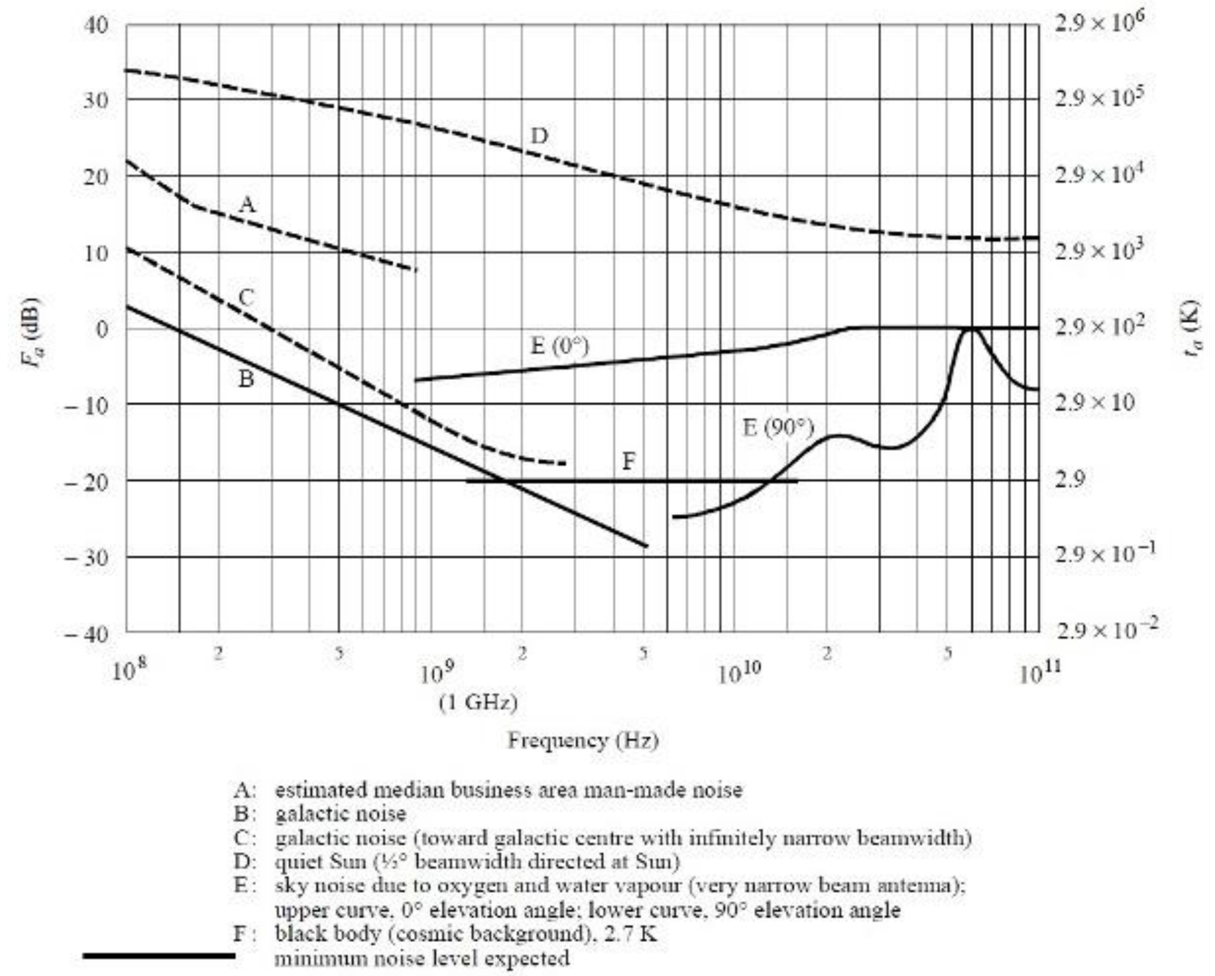


Fig. 10: Power trend of natural and artificial noise as a function of frequency. The estimated levels in the range from 100 MHz to 100 GHz are reported (Recomm. ITU-R P.372-7 "Radio Noise").

The graph in Fig. 10 highlights the interesting fact that the intensity of artificial and natural disturbances decreases as the frequency increases: for this reason, it is not recommended to install a radio telescope, operating in the 10-12 GHz frequency band, in your "back yard", if you live in an urban area, while reception at lower frequencies is very difficult. In the latter case, it will be necessary to choose a rural area, electromagnetically quiet if possible. Indeed, the choices based on the analysis of the spectrum of radio sources are in contrast with those deriving from the analysis of the spectrum of disturbances: this means that advantages and disadvantages are at a level playing field. Technological and economic factors will be crucial.

An amateur radio telescope should be easy to build, cheap and immediately operational: the core of the instrument should be a specially designed radio astronomy module that integrates the essential parts of a basic radio astronomy receiver. The experimenter completes the radio telescope using cheap and easily available commercial components and modules. This is possible thanks to the diffusion of satellite TV reception in the 10-12 GHz band and the availability of antennas, amplifiers, cables and accessories (new and salvaged), suitable for building a perfect amateur radio telescope.

We have already highlighted how the dimensions of the antenna are crucial for the performance and for the final cost of the instrument. The market availability of this delicate component also plays a fundamental role. If we consider that, given the same antenna gain (ability to pick up weak signals in certain directions of space), its dimensions (hence the weight and bulk) decrease as the frequency increases, we understand how it is possible, as well as simple and cheap, to build our first radio telescope using a common parabolic reflector antenna for TV-SAT, a more cost-effective solution in terms of performance/dimension ratio. The only disadvantage remains the limited number of radio sources detectable at these frequencies: small diameter antennas will only be able to detect the Sun and the Moon. However, their radiation is very intense, making these celestial bodies an excellent starting case study in order to familiarize with the instruments and techniques of radio astronomy, in preparation for more demanding observations. To record weaker radio sources, such as Taurus, Cassiopeia, Cygnus and Virgo, larger antennas are needed, while the rest of the system can remain unchanged.

5. The antenna

The antenna transforms the incident electromagnetic energy in what we call potential difference, amplified and processed by the receiver. The function of the antenna is similar to that performed by a lens or an optical instrument's mirror: the performance of the instrument (and its costs) has a leading role. This is a very broad and specialized topic which we will address only in the few essential aspects useful for understanding the process of measuring the *brightness temperature* of the sky, with a simple Total-Power radio telescope.

The study of antennas derives from the theory of electromagnetic radiation and from the analysis of electromagnetic fields generated by sources in free space. The mechanism of radiation is none other than the energy of electromagnetic waves released by the sources and transported over great distances due to propagation. The term *directivity* is used to quantify the ability of an antenna to receive energy from a privileged direction, while the main distinctive parameter is the *effective area*, i.e., the ratio between the power delivered to the receiver and the incident power density in conditions of adaptation. This parameter therefore represents the ideal surface of an antenna from which useful power is obtained, by extracting it from the incident radiation. The effective area depends only on the characteristics of the antenna and is a quantity that measures its efficiency as a collector of radio waves. An elementary antenna is sensitive only to a polarized component of the incident random radiation (vertical or horizontal, right or left circular), extracting only 50% of the energy from it.

The obvious advantage of a directive antenna consists in its ability to eliminate signal contributions from unwanted directions, improving the reception quality in the direction of interest. Another very important feature is the *resolving power*, i.e., the ability to separate (resolve) two close objects, thus observing small structural details of an extended radio source, a parameter proportional to the relationship between the wavelength of the radiation received and the physical dimensions of the antenna. These characteristics of the antenna define the performance of the radio telescope.

The paraboloid reflector, characterized by a very narrow and symmetrical reception lobe, is a widely used antenna in the microwave band. Its qualities derive from the focusing properties of the dish: the energy captured, coming from a distant source, is reflected by the surface of the reflector and focused in a point where the external LNB reception unit is positioned. The possibility of having only one focal point is very interesting: if the collection device (illuminator) is well positioned, all the incident electromagnetic energy captured by the reflector will be used to extract the useful signal. To estimate the gain obtained from a parabolic reflector antenna one can use the following equation:

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

where D is the diameter of the antenna (expressed in meters). The parameter ε is called efficiency: comprised generally between 0.45 and 0.55, it takes into account all the factors that reduce the maximum obtainable theoretical gain (surface errors, construction tolerances, focusing errors, excessive width of the secondary lobes). The half power beamwidth HPBW (*Half Power Beam Width*) can be calculated using the following approximated formula:

$$HPBW \cong \frac{(60 \div 70)\lambda}{D} \quad [gradi]$$

These relationships show that the gain of the antenna is directly proportional to its size, the opposite happens for the width of the reception beam: an antenna with a high gain will have a narrow reception beam and will therefore be more directive.

The possible structures of an antenna system vary greatly according to the operating frequency and type of application. At lower frequencies the antennas are mainly of the wired type (metal dipoles), while at high frequencies (microwaves) they consist of radiating elements which can be more easily connected with waveguides (horn, slit antennas) and with optical systems (parabolic reflector antennas). In professional radio astronomy, composite systems are composed by many elements (arrays) and/or optical focusing elements (reflectors, lenses): The dimensions must always be much greater than the operating wavelength, at low frequencies, which entails the creation of impressive structures in terms of complexity and costs.

The antenna temperature represents the signal power which is actually available at the receiver input, therefore a measure of the energy captured by a specific region of the sky that radiates with a given brightness temperature. During measurement it is important to consider the spatial filtering effect produced by the shape of the antenna reception diagram: this operation is mathematically described by the *convolution* between the functions that describe the directive properties of the structure and the brightness profile of the observed scenario. The antenna of a radio telescope therefore tends to “level” and “dilute” the real brightness distribution which will be assessed by the shape of its reception diagram. The measurement of the observed spatial variations of brightness will approximate the real one only if the angular dimensions of the radio source are extended with respect to those of the antenna beam. The observer’s problem is now obtaining the true distribution of the brightness temperature starting from the measurement of the antenna temperature: it is necessary to carry out a *de-convolution* operation between the distribution of the equivalent antenna temperature (measured brightness) and the function describing its reception diagram. For these reasons it is very important to know the shape of the directive diagram of a radio telescope.

All the space surrounding an antenna contributes to increasing its equivalent noise temperature, according to its directive characteristics. If the antenna secondary lobes’ level is too high, by orienting the main lobe towards a given region of space the antenna temperature can receive a non-negligible energy contribution coming from other directions, in particular from the ground (very large and hot object with a brightness temperature of the order of 240-300 K). If the antenna is oriented towards the sky, it can pick up thermal radiation from the ground only through its secondary lobes: this contribution depends on their amplitude compared to that of the main lobe.

Fig. 10 shows the traces (simulated and real) of the transit of the Moon (flux of the order of 52600 Jy at 10-12 GHz) recorded by an amateur radio telescope based on RAL10KIT and a TV-SAT parabolic reflector antenna with 1.5 meters in diameter (beam width just under 1.5 degrees).

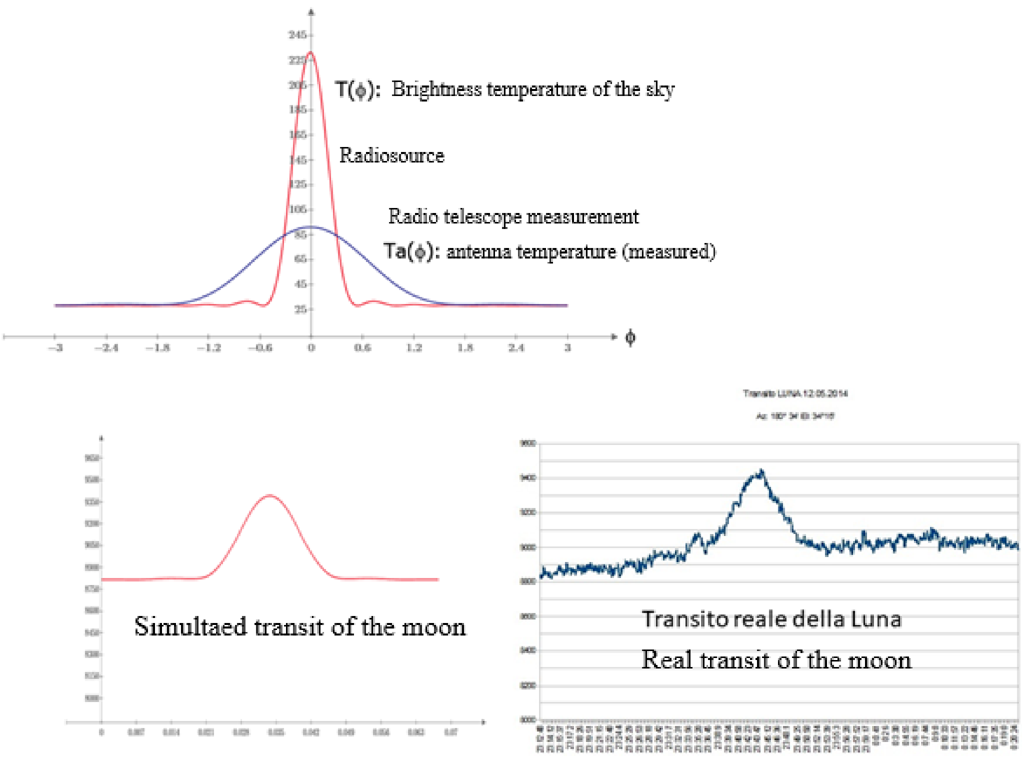


Fig. 10: The temperature profile of the Moon detected by a radio telescope (antenna temperature) during a transit is different from the "true" profile of its brightness temperature, given that the measurement process performed with the antenna is a convolution between the true brightness of the observed scenario and the shape of its reception diagram. The antenna of a radio telescope "dilutes" the observed brightness distribution: the extent of the distortion is due to the spatial filtering characteristics of the antenna and is linked to the ratio between the angular dimensions of the receiving beam and the apparent ones of the radio source. No distortion occurs if the antenna reception pattern is very narrow compared to the angular extent of the source. The graphs show a comparison between the simulated recording of the lunar transit and the real observation (carried out by Mr. Giancarlo Madiai with *RAL10KIT*).

In conclusion, when we analyse the recording of the transit of a radio source, we observe a trace that does not correspond to the true brightness profile of the scenario, but to a distorted version of it, a convolution between the shape of the radio telescope reception diagram and the real brightness distribution. The greater the amplitude of the antenna reception beam with respect to the apparent angular dimensions of the radio source, the greater the effect. On the contrary, the spatial profile of the brightness temperature of the radio source is measured without distortions only if its angular dimensions are very large compared to the width of the antenna beam. It is understood how this is a relevant problem for amateur radio telescopes that use single antennas of small dimensions, with reception lobe widths comparable to the angular dimensions of radio sources such as the Sun and the Moon (about half a degree), or much larger than all other radio sources which can rightfully be considered punctiform when observed with these instruments. The one exception is our Galaxy, which, if observed in the radio band, is characterized by a remarkable angular extension.

6. The total power radiometer

A microwave radiometer is a very sensitive receiver used to measure the intensity of the electromagnetic radiation captured by the antenna, within a specific frequency band, showing how the power of the received signal varies over time.

Any body with a temperature above absolute zero emits electromagnetic energy (*Planck's Law of Radiation*) throughout the spectrum, with a maximum at a frequency directly proportional to its temperature. Planck's law describes the radiation of a *black body*, an ideal object that is perfectly efficient at transforming all of its thermal energy into electromagnetic radiation. In the microwave region, Planck's law is simplified in *Rayleigh-Jeans' approximation* which provides a correspondence between the power of radiant energy captured by the antenna of a radiometer and the measured antenna temperature, a quantity which depends on the source and characteristics of the measuring instrument and the surrounding environment. The antenna temperature will correspond to the effective brightness temperature of the observed scenario (specific emissive characteristic of the source) only in ideal conditions, i.e., when the antenna beam is very small compared to the observed brightness spatial distribution and when the noise contributions coming from its secondary lobes (ground, interfering sources) 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 (in Kelvin) to indicate the amount of its thermal radiation.

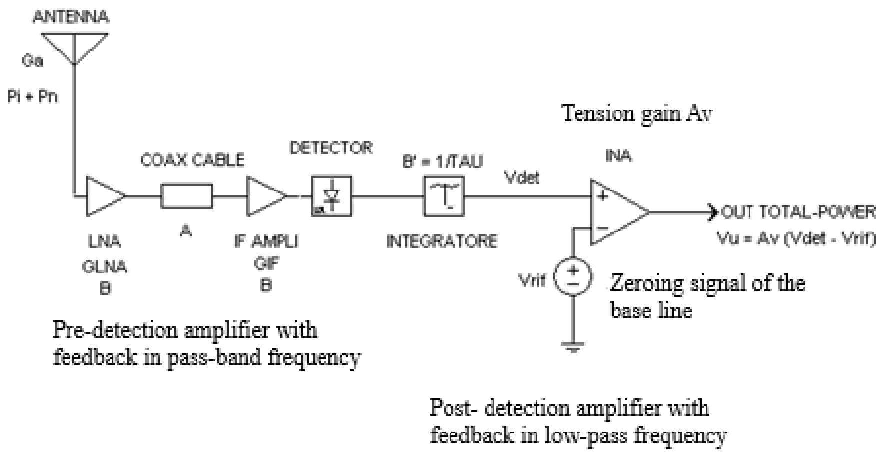


Fig. 11: Basic scheme of a Total-Power receiver.

Basically, it is always possible to define the temperature of a black body (brightness temperature) which radiates the same power as that dissipated by a terminating resistor connected to a receiving antenna. Therefore, the radiometer behaves like a thermometer that measures the brightness temperature of the observed celestial scenario.

The simplest microwave radiometer (Fig. 11) consists of an antenna connected to a low noise amplifier followed by a quadratic characteristic detector which supplies the useful information, i.e., the power associated with the received signal. To reduce the contribution of the statistical fluctuations of the detected signal, and therefore optimize the sensitivity of the receiving system, an integrator block follows (a low-pass filter) which calculates the average time of the measurement according to a given time constant. The signal at the integrator output appears as a quasi-continuous component due to the average value of the background noise of the receiver to which small variations are superimposed (generally of an amplitude much lower than that of the stationary component) due to the emissions of radio sources. The instrument is called a *total power receiver (Total-Power)* because its response is the sum of the power deriving from the radiation captured by the antenna and the background noise of the system. Using a post-detection differential circuit, if the receiver parameters remain stable, only the power variations due to the radiation coming from the antenna are measured, eliminating the quasi-continuous component due to internal noise.

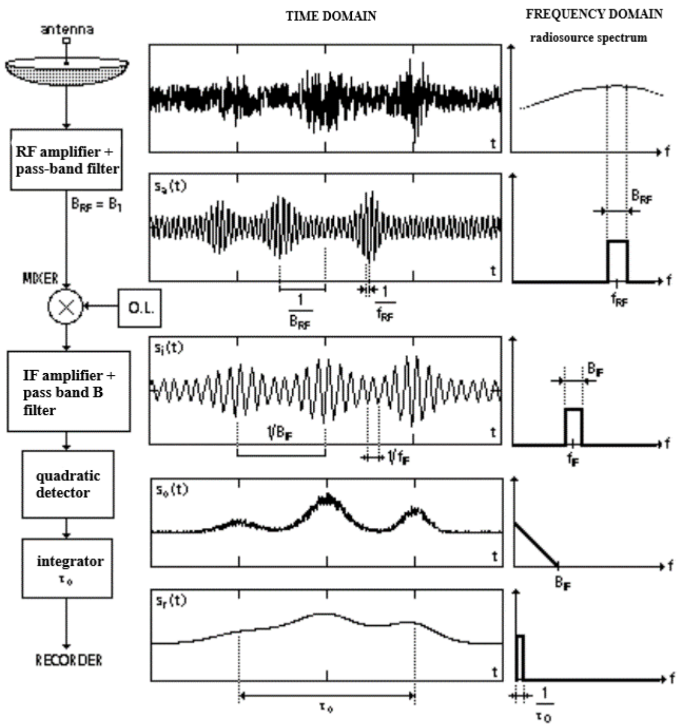


Fig. 12: Variations of the signal picked up by the antenna as it is processed by the various stages of a full power receiver. On the left the signals as a function of time at a given frequency, on the right the variation of power as a function of frequency (spectrum). The block diagram of the receiver represents a frequency conversion structure: the received signal is translated in frequency (downward) through a mixer driven by the local oscillator (OL). An intermediate frequency (IF) signal is found at the output of the mixer which is subsequently amplified, revealed and integrated.

The circuit configuration used is the frequency conversion one (heterodyne), where the signal picked up by the antenna, amplified and filtered by low noise electronic devices, is applied to a multiplier (mixer) which, fed by a sinusoidal signal coming by a local oscillator (OL), performs the frequency translation (downwards) of the received signal. In this way it will be technically easy to define the passband of the receiver and to amplify the signal before detection. A schematization of the signals during processing in the various stages of a frequency conversion Total-Power receiver is shown in Fig. 12. The quadratic detection process and the subsequent integration do not preserve the spectral characteristics of the signal: they provide a single value representing its average power within the receiver passband. If broadband and stable receivers are used (the amplification factor of the system and the characteristic of the detector should not vary during the measurement) very high sensitivities are reached, also thanks to the possibility of integrating the detected signal with long time constants, admitted that the phenomenon object of the study is sufficiently stationary in time.

Estimating the theoretical sensitivity of a Total-Power receiver, then evaluate the minimum variation in the noise equivalent temperature ΔT measurable by the system, is possible by using *the radiometer equation*:

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

where

$$T_{sys} = T_a + T_r = T_a + T_0(F_r - 1)$$

Is the noise temperature of the radio telescope, T_a is the noise temperature of the antenna, $T_r = T_0\ (F_r - 1)$ is the noise temperature of the receiver ($T_0 = 290\ K$ and F_r is the figure that indicates the receiver's noise), τ is the time constant of the integrator (in seconds) and B is the bandwidth of the receiver (in Hz). The temperatures are expressed in K. Any radio source picked up by the antenna will produce a small variation in the antenna temperature T_a which represents our useful signal.

To optimize the performance of the radio telescope it is desirable to minimize ΔT by acting on the system parameters T_a, T_r, B in the projecting phase, on the integration time τ during operation (T_{sys} should be minimal, B and τ as large as possible). Therefore, once the receiver parameters have been fixed, the sensitivity is optimized by choosing a suitable value for the integration constant of the detected signal. Increasing this parameter means applying a low-pass filter on the variability characteristics of the observed phenomenon: the variations of the signal with a time-span shorter than τ are hidden and the information on the temporal evolution of the quantity studied is altered (or lost). For a correct recording of phenomena with variations of a certain duration, it is essential to set a value for the integration constant that is sufficiently lower than this duration. If, for example, a radio source with a small apparent diameter which passes through the main lobe of a radio telescope (transit instrument) is observed in a certain time-span, it is not possible to integrate the detected signal with a too large time constant, without modifying the received signal strength and apparent time of transit. The maximum usable value for the integration time applicable to a signal characterized by temporal variability of the order of ΔT is given by the following approximate relationship:

$$\tau \leq 0.35 \cdot \Delta T$$

Time is expressed in seconds. This relationship is based on the consideration that, in order to maintain the characteristics of variability of the integrated signal, eliminating most of the disturbances and superimposed high-frequency noise, it is necessary to integrate this signal with a time constant so that the equivalent noise band of the integrator (low-pass filter) is approximately equal to the signal band occupation.

The main problem of radiometric measurements concerns the instability of the receiver parameters with respect to variations in ambient temperature. Since the overall amplification of the instrument is very high, typically higher than 100 dB, it is easy to observe fluctuations in the output signal, due to minimal variations in the receiver parameters, which produce ambiguity and limit the sensitivity and accuracy of the measurements. This problem can be solved, with satisfactory results in amateur applications, by thermally stabilizing the receiver and the external electronic unit (LNB) placed on the focal point of the antenna, therefore more exposed to daily temperature variations. It may be useful to develop compensation procedures for the "after" thermal drifts on the acquired data, measuring the internal temperature of the instrument, characterizing the behaviour of the receiver with respect to the daily temperature excursions and implementing a compensation algorithm on the acquired radiometric samples tending to minimize the variations of the instrumental response due to the temperature.

7. Building a radio telescope Total-Power in the 10-12 GHz band

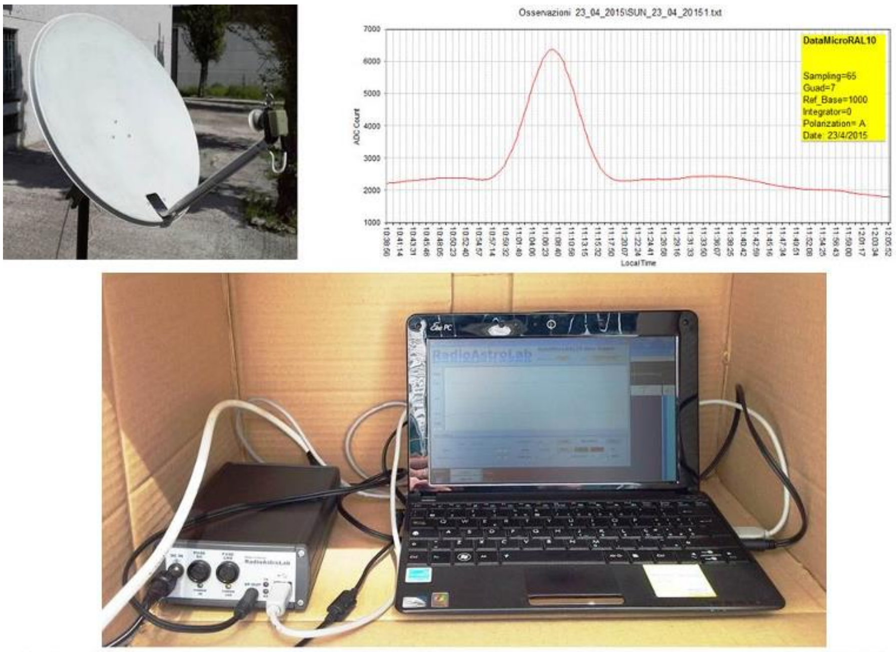
We will describe how to assemble a small but efficient radio telescope operating in the 10-12 GHz band, equipped with a standard parabolic reflector TV-SAT antenna, capable of measuring the brightness temperature of the Sun and the Moon, highlighting the thermal radiation of the sun (at these frequencies the most intense phenomena are detectable) and the interstellar medium in the galaxy, the radiation of the earth's atmosphere. This instrument can be considered the starting point of amateur radio astronomy and excellent “training” to familiarize with radio astronomy techniques. Just a simple calibration procedure is necessary to transform the radio telescope into a measuring instrument that estimates the brightness temperature of the observed scenario. To observe other objects, it will only be necessary to use larger antennas.

An instrument of this type is cheap and easy to install: having made the few necessary connections (coaxial cable which carries the signal from the antenna to the receiver, USB cable for connection to the acquisition PC and power supply) one is immediately ready for radio- observations. The central nucleus on which the radio telescope’s functioning is based on is a full power radiometer. Our project involves the use of microwave receivers specially developed for this application: the *RAL10KIT* module or the *RAL10AP* receiver, combined with the *ARIES* acquisition and control software. The following components are required:

- • TV-SAT parabolic reflector antenna, complete with external unit (LNB) and illuminator;
- 75 Ω coaxial cable for TV-SAT;
- *RAL10KIT* module or *RAL10AP* receiver;
- Software for acquiring measurements and for controlling the *ARIES* receiver;
- Personal Computer (PC) for station management.

The antenna, the external unit (LNB) and the coaxial cable are standard components used for the reception of satellite TV, available at low cost. Any model is fine: all devices can be used with the *RAL10KIT* or with the *RAL10AP* receiver. As far as the antenna is concerned, the satellite TV market offers many choices: the most common ones are offset parabolic antennas, due to the better performance/size ratio they offer compared to symmetrical circular ones. It is important to use kits which include, in a single package, external units (LNB) complete with illuminators and supports suitable for the specific antenna, and which guarantee correct focusing for the specific type of reflector.

Using one’s imagination and constructive ability it is possible to create automatic pointing systems, at least for antennas that are not too large, drawing on the amateur radio equipment market. The small size and low weight of this radio telescope makes it possible to use a manual or motorized (equatorial) assembly, like the type normally used by amateur astronomers to support and orient optical instruments. In this case there is plenty of room for imagination and ingenuity in designing a coupling system for this assembly, replacing 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 creating a practical and efficient solution for measuring and tracking the solar radio flux. There are many examples of interesting and ingenious creations on the web. The mapping programs of the celestial vault can be very useful for correct pointing and for planning observation sessions, as they reproduce, in any location, date and time, the exact position and movements of celestial bodies with remarkable detail and precision.



Tests of radio astronomy @ 11.2 GHz : the radio signals from the Sun with RAL10AP.

Fig. 13: Test of reception of the Sun with the receiver *RAL10AP*.

As mentioned, practically all external units (LNB) existing on the market for 10-12 GHz TV-SAT with intermediate frequency output 950-2250 MHz can be used. In modern devices it is possible to manage the change of polarization (horizontal or vertical) with a voltage jump, typically 12.75-17.25 V and the switching of the reception band (LOW BAND/HIGH BAND) by injecting a 22 kHz tone along the coaxial line: the *RAL10KIT* and *RAL10AP* receivers support these functions via software commands. A 75 Ω TV-SAT coaxial cable of suitable length, terminating with type F connectors, will connect the RF-IF output of the external unit (LNB) with the input of the *RAL10KIT* or *RAL10AP* receiver. It is recommended to choose the best quality, low loss cables. In some cases, when radio sources of weak intensity are observed or when the coaxial line is very long, it may be useful to insert an IF line amplifier (10 to 15 dB of gain) between the external unit and the receiver. These products are easily available in any consumer electronics supermarket or at the best TV-SAT system installers. Fig. 13 shows an example of a solar transit recorded with our radio telescope.

8. The radiometric module

Let us briefly describe the characteristics of the radiometric module which forms the core of the *RAL10KIT* and *RAL10AP* radiometers. Fig. 14 shows the block diagram of the device.

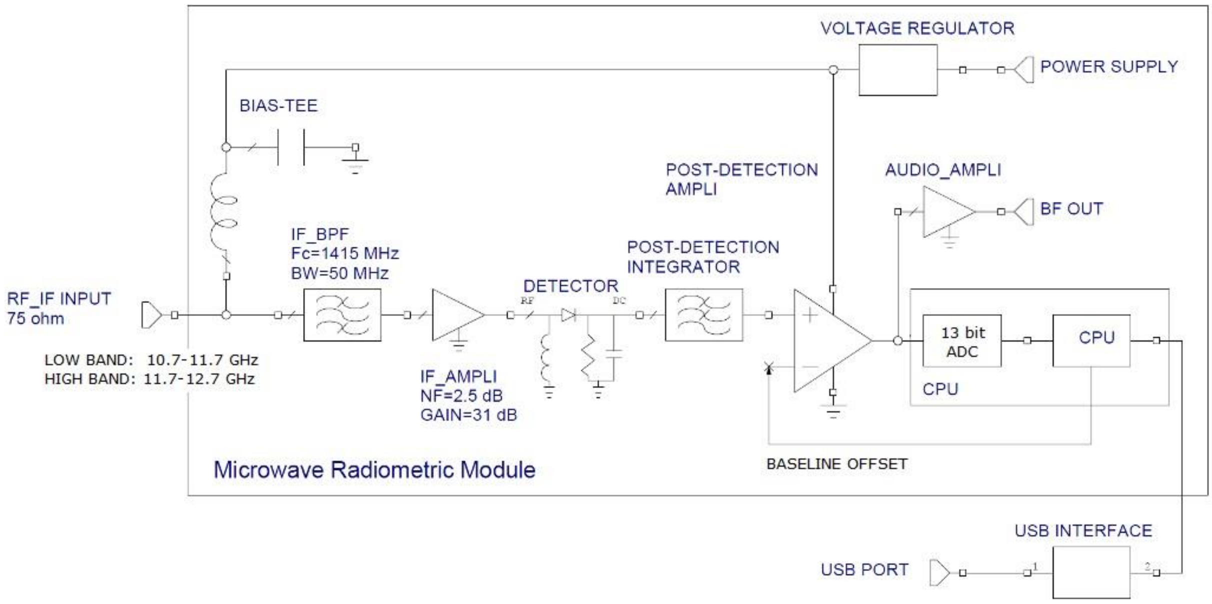


Fig. 14: Block diagram of the radiometric module, the core of the *RAL10KIT* e *RAL10AP* receivers.

The intermediate frequency (IF) signal coming from the external unit (LNB) is applied to the module which, with a passband of 50 MHz tuned in the 1415 MHz frequency, filters, amplifies and measures the power of the received signal (detector block). If the external unit provides for it, it is possible to select the reception band (LOW BAND-HIGH BAND) by injecting a 22 kHz tone through the input coaxial cable.

A post-detection amplifier adapts the level of the detected signal to the acquisition dynamics of the analogue-to-digital converter (ADC with 13-bit resolution) which "digitizes" the radiometric information. This final block, managed by a processor, generates a programmable offset for the radiometric baseline, calculates the average value over a set number of samples and forms the serial data packet which will be transmitted to the PC. The data acquired from the radiometric measurements and the operating parameters of the radiometer are managed by a proprietary communication protocol through the serial port (USB). An internal non-volatile memory allows the recording of the optimal settings of the operating parameters: once the system has been calibrated for a particular application, if the command to record the set parameters is sent, their values are preserved when the power is removed and restored. The processor performs processing and control functions while minimizing the number of external electronic components and maximizing system flexibility. The AUDIO output of the detected signal is present only in the *RAL10AP* model. The use of a module specifically designed for radio astronomy, which integrates all the functions required by a radiometer, guarantees the experimenter a safe and repeatable performance: it is the central block of the *RAL10KIT* and *RAL10AP* receivers which, therefore, have identical performance.

Assuming to use a good quality external unit (LNB), with a noise figure of the order of 0.3 dB and an average gain of 55 dB, we obtain the receiver’s equivalent noise temperature of the order of 21 K and a power gain of the radio frequency chain of about 75 dB. These performances are more than adequate to build an amateur radio telescope. The sensitivity of the system will, however, depend on the dimensions of the antenna, while the external thermal excursions will influence the stability and repeatability of the measurement. The experimenter's imagination and skill are crucial to optimizing the performance of an amateur radio telescope: a correct choice and adequate installation of the critical radio frequency parts (antenna, illuminator and LNB), along with the implementation of countermeasures that minimize the negative effects of thermal excursions, ensure important advantages in final performance.

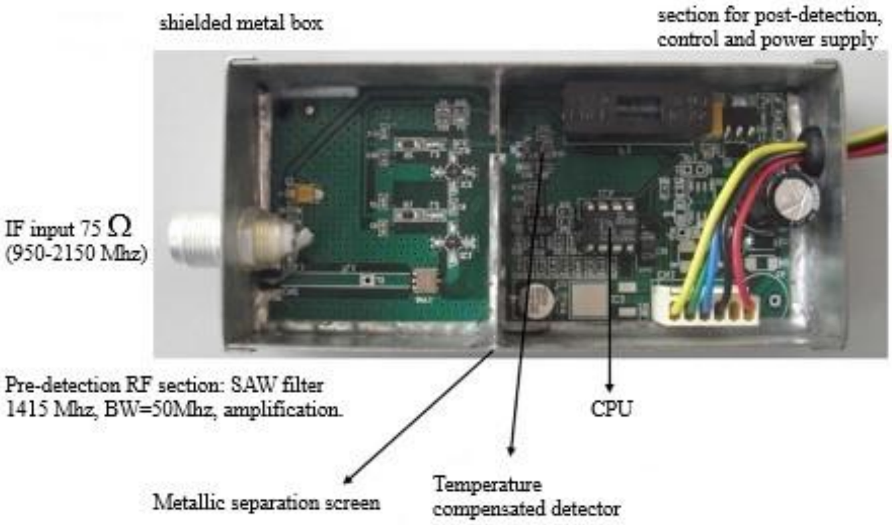


Fig. 15: Internal details of the radiometric module.

Technical characteristics of the radiometric module:

- Input centre frequency RF-IF: 1415 MHz;
- Bandwidth: 50 MHz;
- Typical section gain RF-IF: 20 dB;
- Input impedance (F-type connector): 75 Ω;
- Polarization selection (horizontal or vertical);
- Selection of the LNB reception band (LOW BAND – HIGH BAND);
- Temperature compensated quadratic detector (measurement of RF power).
- Setting the offset for the radiometric baseline;
- Automatic calibration of the radiometric baseline;
- Programmable post-detection voltage gain: from 42 to 1008 in 10 steps.
- Programmable integration constant (from 0.1 seconds up to 26 seconds);
- Acquisition of the radiometric signal with 13-bit ADC.
- Processor that controls the receiving system and manages the serial communication.
- Storage of radiometer parameters (internal non-volatile memory).
- USB interface (type B connector) for connection to PC.
- Compatible with ARIES acquisition and control software.
- Supply voltages: 7-12 VDC / 50 mA.
- Power supply for LNB through coaxial cable, protected with internal fuse.

The electronics are assembled inside a metal box containing an F-type coaxial connector for the signal coming from the external unit (LNB) and a cable gland to which the cables for serial communication and those for connection to the feeder are connected (Fig. 15). As mentioned, it is possible to set the operating parameters of the radiometer via software using appropriate commands encoded in the communication protocol of the device, automatically managed by the *ARIES* software. These parameters are:

- *ZERO_BASE:* is a value proportional to the reference voltage V_{rif}, shown in the principal diagram of the total power radiometer in Fig. 11, used to set an offset on the radiometric baseline. It is possible to automatically adjust the value of *ZERO_BASE* by activating the calibration procedure which positions the reference level of the received signal (that corresponds to "zero") at the centre of the measurement scale.

- *GAIN*: it is the amplification factor of the detected signal.

- *INTEGRATOR*: is the value of the integration constant τ of the radiometric measurement, resulting from the calculation of a moving average performed on the $N=2^{INTEGRATOR}$ acquired signal samples. Increasing this value reduces the importance of the statistical noise fluctuation on the measurement, improving the sensitivity of the system. As for any measurement integration process, it is necessary to consider a delay in signal recording related to the sampling time of the information, the conversion time of the analogue-to-digital converter and the number of samples used to calculate the average. Using the table in Fig. 16 it is possible to estimate the value of the time constant τ (expressed in seconds).

INTEGRATOR	Time constant τ of the integrator [*S*]
0	0.1
1	0.2
2	0.4
3	0.8
4	2
5	3
6	7
7	13
8	26

Fig. 16: Integrator time constant in function of the value set for the *INTEGRATOR* parameter.

- POL selects the reception polarization used in the outdoor unit (LNB).

- BAND: select the reception band of the external unit (LOW BAND = 10.7-11.7 GHz, HIGH BAND = 11.7-12.7 GHz).

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

8. RAL10KIT

RAL10KIT is a radio astronomy module dedicated to experimenters with a minimum experience in electronic assemblies who wish to build "home-made" receiver for their radio telescope. The package includes a radiometric module, a USB interface card for connection to the PC, assembly instructions and the *ARIES* software for acquiring and controlling the radiometer. The modules are assembled and tested: it is sufficient to enclose everything in a suitable container, complete it with a power supply, a coaxial cable and an antenna with an external unit (LNB) operating in the 10-12 GHz TV-SAT band. The first microwave radio telescope (Fig. 19).

Fig. 17: Radioastronomy kit *RAL10KIT* provided by RadioAstroLab.

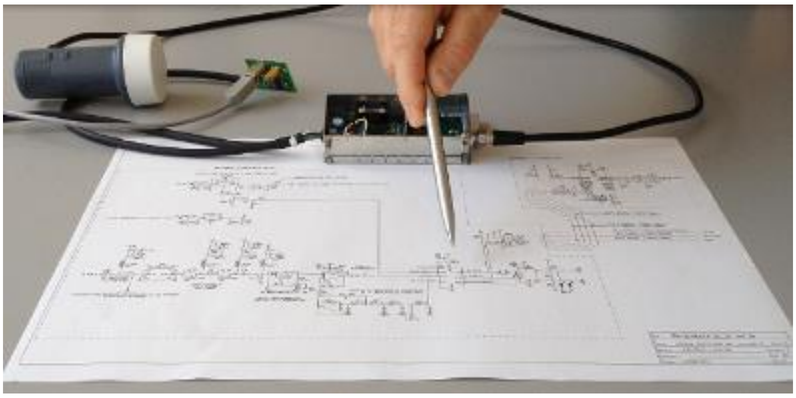


Fig. 18: Radioastronomy kit *RAL10KIT*: the radiometric module is the nucleus of the receiver.

Fig. 20 shows the wiring diagram of the *RAL10KIT* group and the information necessary for connecting the power supply cables: it is possible to use any well-filtered stabilized power supply, suitable for supplying the specified voltages and currents. It is advisable to enclose the modules, including the power supply, in a metal container which forms a shield for the receiver. As illustrated in the diagram, the USB interface module has been designed for panel mounting: it will be necessary to prepare holes and slots for the fixing screws, for the red and green LEDs which signal the serial communication activity and for the USB type B.

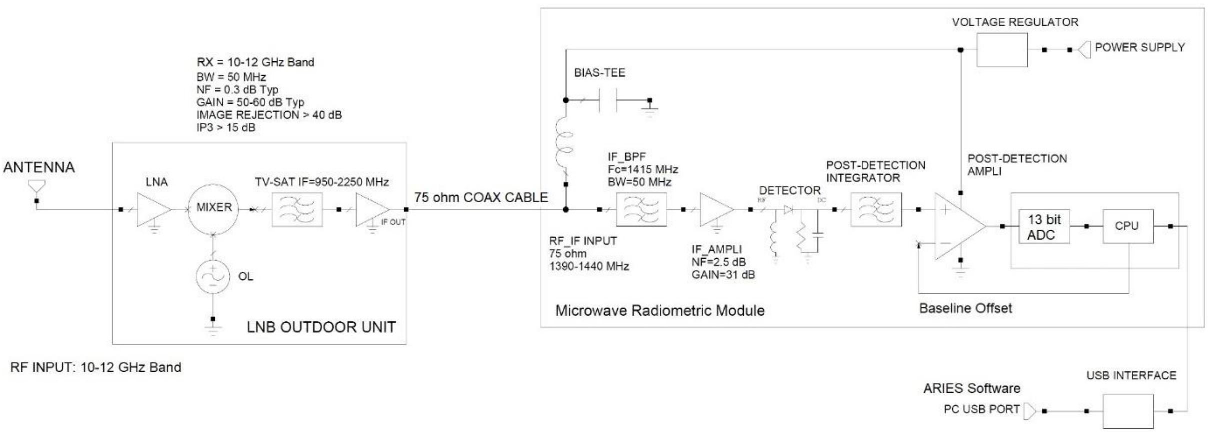


Fig. 19: Structure of a microwave radio telescope (10-12 GHz band) built with *RAL10KIT*. The signal received from the parabolic antenna, amplified and converted into frequency by the external unit (LNB) towards the standard TV-SAT 950-2250 MHz IF band, is applied to the *RAL10KIT* unit which processes all the information and transmits it to the PC via a USB serial channel. The *ARIES* software acquires the radiometric measurements, displays the data as a graphic recorder and controls the operating parameters of the receiver.

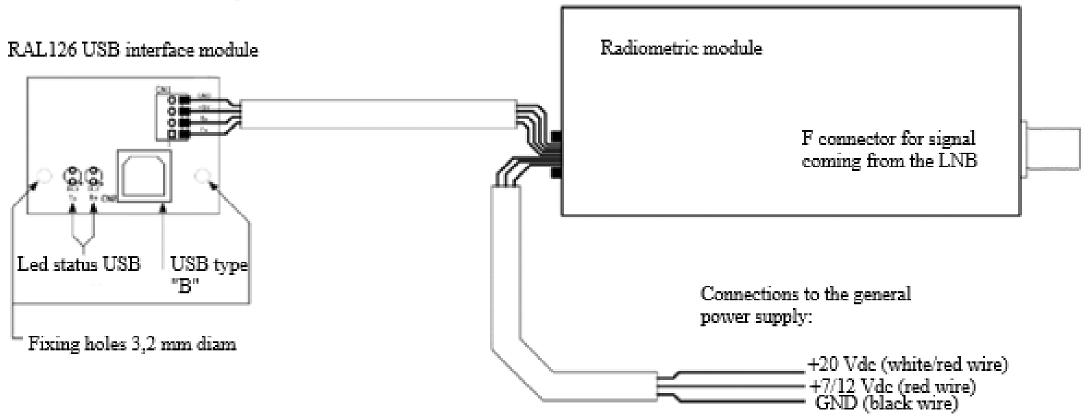


Fig. 20: Wiring diagram of the *RAL10KIT* group: the radiometric module (supplied assembled and tested) is contained inside a shielded metal box which has an F coaxial connector for connection to the signal coming from the external unit (LNB) (via coaxial cable 75 Ω for TV-SAT) and a rubber cable gland from which the connections for the USB interface and the power supply come out.

9. RAL10AP receiver

The microwave receiver *RAL10AP* is a complete and simple to use total power radiometer, a ready-to-use instrument enclosed in an elegant and compact anodized aluminium container, supplied with an external 12V-2A power supply. It is possible to power the device with a battery to facilitate "field" measurements, in remote locations where mains power is not available. Located on the front panel are the protection fuses (with interruption signalled by LEDs) for the main power supply and for the power supply of the external unit (LNB) through the coaxial cable (Fig. 21).

Fig. 21: *RAL10AP* receiver: note (above) the socket for the 12 VDC general power supply, the fuse holders with LED-indicated interruption for the general power supply and for the power supply of the LNB external unit via the coaxial cable (the lights go off when the respective fuse is blown), the post-detection audio output (BF-OUT) and the USB port for connection to the PC (the LEDs indicate the data flow). On the rear panel (bottom) the F connector for signal input (IN RF) coming from the external unit.

The input of the instrument accepts frequencies included in the 1390-1440 MHz band, with characteristics identical to those of the previously described *RAL10KIT* module. An interesting option, available only for the *RAL10AP*, concerns the post-detection audio output: it is possible to apply a detected signal to an external amplifier or to the input of a PC sound card in order to listen to the detected noise for monitoring. This signal, proportional to the power density of the received signal, can be studied in the frequency domain using one of the many free programs downloadable from the web which display spectrograms in the audio band. As shown by the block diagram of Fig. 14, the audio output is taken after the post-detection amplifier, therefore its level depends on the calibration level of the radiometric baseline. Audio noise can be heard through the PC speakers.

10. Operational parameter setting

The signal level at the radio telescope output is proportional to the power associated with the received radiation, therefore to the *brightness temperature* of the sky area observed by the antenna. If the antenna is oriented towards a region of clear and dry sky where there are no radio sources, the instrument measures a very low equivalent noise temperature, generally of the order of 6-10 K (the so-called *cold sky*), corresponding to the minimum temperature measurable. By directing the antenna towards the ground, the temperature rises reaching values of the order of 300 K. This simple procedure illustrates, in an approximate and simplified way, the technique that can be used to calibrate the radio telescope, representing an excellent test to verify its efficiency.

When a typical amateur radio telescope is oriented towards the Sun, which at the frequencies of our interest appears as a disk about half a degree wide and radiates as a black body with a brightness temperature approximately equal to the one on surface (6000 K), we expect an antenna measurement temperature of the order of 300-400 K, a much lower value than the real one. In fact, the cosmic background radiation, captured in good percentage by the outermost corona of the antenna lobe, “dissolves” the powerful solar radiation if the antenna beam is wide enough to collect a significant contribution and decreases the amplitude of the signal received, as if it came from a source with a much lower temperature than the real one, as previously described.

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

First you need to power up the receiver and wait for the instrument to reach thermal balance. The instabilities of the system (the main problem of full power radiometers) are mainly caused by variations in the environment temperature and in the internal temperature of the radiometer: before starting any measurement, it is advisable to wait at least one hour after switching on the instrument to allow the electronic circuit to reach optimal operating temperature. This condition can be verified by observing the long-term stability of the radiometric signal when the antenna points to a "cold" region of the sky (absence of radio sources): the fluctuations displayed by the graphic trace on the *ARIES* program are minimal.

The *GAIN* amplification factor should be set to intermediate values (typically *GAIN*=7). Each installation will be characterized by different performances, since it is impossible to foresee the characteristics of the external components that will be chosen by the users. It is advisable to adjust the value of this parameter starting with minimum test values (to avoid saturation of the receiving system), subsequently optimizing with repeated scans of the same region of the sky. To observe the Sun, it is advisable to choose *GAIN*=7 (or lower values if the signal tends to saturate). To observe the Moon, it is advisable to start with *GAIN*=10. However, these settings are greatly influenced by the size of the antenna and the characteristics of the external unit (LNB) and must always be checked carefully.

Once the amplification factor has been defined, the *INTEGRATOR* integration constant is adjusted to stabilize the measurement. It is advisable to start with minimum values (0.1 seconds), which are adequate in most cases. It is possible (and desirable) to improve the sensitivity of the measurement, at the cost of a slower and delayed system response with respect to signal variations, by adopting a greater time constant: it is advisable to increase the value of this parameter when observing radio sources with relatively stationary emissions. When recording rapidly variable or transient phenomena (such as, for example, microwave solar flares) select the minimum value. It is always possible to further increase the integration of the received signal by adjusting the *SAMPLING* parameter in the *ARIES* program.

The *ZERO_BASE* parameter establishes the reference level (offset) of the radiometric baseline: a correct setting depends on the global amplification of the receiver. As a general rule, *ZERO_BASE* should be chosen so that the minimum signal level corresponds to the *cold sky* (ideal reference) when the antenna observes a region without radio sources: an increase of this reference will indicate the presence of an emitting celestial object. The position of the baseline on the measurement scale is a function of the amplification factor *GAIN* and of the value set for *ZERO_BASE*: if the signal tends to move outside the measurement scale (opening-scale or full-scale) due to internal drifts, you will need to manually change the *ZERO_BASE* value or activate automatic calibration in order to position the trace correctly.

Using suitable external units (LNB) it is possible to modify the reception band and the polarization in reception to observe radio sources where an emission with a polarized component predominates. In most amateur level observations accessible, the radio sources emit a wide spectrum of frequencies with random polarization: in these cases, it may be useful to modify the reception band and/or the polarization to minimize any artificial interference.

When purchasing trade goods for satellite TV reception, the position of the feeder (integrated with the external LNB unit) is generally fixed along the focal line of the antenna. If you want to improve the performance of the radio telescope, you should orient the antenna in the direction of a sample radio source (such as the Sun) and vary the position of the illuminator back and forth along the axis of the parabola in order to register a maximum intensity signal, obviously only if mechanically possible. Repeated measurements and a lot of patience help reduce errors.

Confirmation for a correct setting of the receiver parameters requires some test observations. This procedure, normally also adopted by professional radio-observers, allows the radio telescope to be "calibrated" so that the dynamics of its response and the scale factor are adequate to record the observed phenomenon. If correctly performed, this first setting (necessary above all when planning long periods of observation) will adjust the gain and the offset of the scale for a correct measurement, avoiding the risk of saturation or zeroing of the signal, with consequent loss of information. Once the initial setup is complete, it is preferable to memorize the radiometer settings using the appropriate command.

Always remember that the main factor limiting the stability and accuracy of the radiometric response is the temperature excursion experienced by the radiometer, especially by the external unit (LNB): these temperature variations cause minimal variations in the front-end gain and in the internal parameters of the instrument sufficient to cause significant fluctuations in the reference level, given the large amplification of the system. The best radio telescope performance is obtained when the receiver is thermally stabilized. This is a key condition for the quality of the measurements.

As anticipated, the simplest radio astronomy observation involves orienting the antenna towards the south and positioning it at an elevation sufficient to intercept a specific radio source during its transit at the meridian, i.e., the apparent passage of the object through the local meridian (the one that contains the poles and the installation point of the radio telescope). By setting a sufficiently slow sampling period in the *ARIES* acquisition program (for example, a screen shot every 24 hours), it is possible to verify whether, during the day, the antenna intercepts the desired radio source and whether the values chosen for the parameters are adequate to document the observation. You may need to increase the amplification factor to see more trace detail, or change the baseline level to prevent the signal from going off-scale somewhere on the graph. Once the setup procedure is complete, you can start long unattended automatic recording sessions.

11. The control and acquisition software ARIES

ARIES (Fig. 22) is an advanced and user-friendly Personal Computer (PC) program, developed to manage the automatic acquisition and control of the Total-Power microwave receivers of the *RAL10* series. The program, conceived to optimize the robustness and flexibility in the communication of these devices, controls the operating parameters of the specific model used: the trend of the measurements over time is displayed in the style of a graphic recorder and the information is acquired according to various methods and formats. The variation of the acquired data is displayed as a moving red trace, represented in a rectangular diagram where the abscissa is the time variable (expressed in Local Time or in UTC time) and the ordinate is the intensity of the signal expressed in relative *ADC_count* units. Since a calibration procedure management of the received signal in absolute units of brightness temperature is not currently available, the intensities of the radiometric signals are displayed in counting units of the internal analogue-digital converter (ADC), on a 0 to 8191 scale (13-bit measurement resolution).

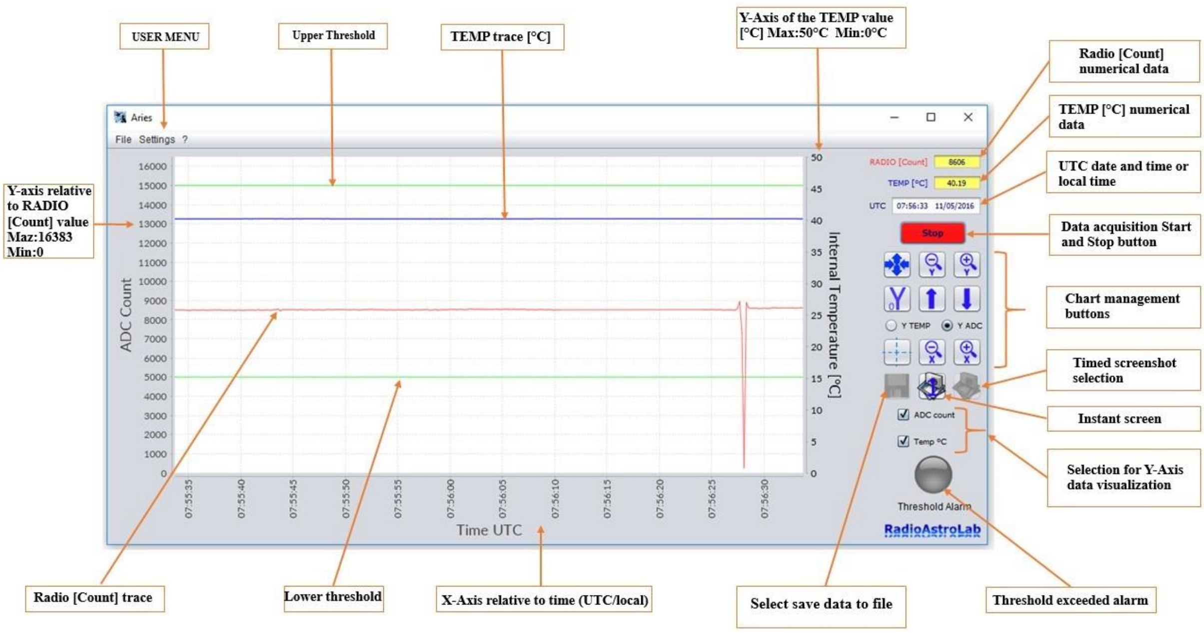


Fig. 22: Main window of the *ARIES* program (The settings are referred to the *RAL10*).

With *ARIES* it is possible to control all the parameters of a single receiver in a simple and immediate way, or to manage different and simultaneous measurement sessions with several devices (even of the same type) connected to a single PC: the communication protocol implemented in the instruments and the program interface allows very reliable communication management, perfect even in applications that require continuous measurements for a long time-span and in remote locations not monitored by operators.

Conceived as a data acquisition system for amateur radio astronomy stations, *ARIES* includes everything needed to manage and display the measurements, with a wide range of possibilities for setting the graphic scales and programming the operating parameters. The ability to automatically record data and the ability to set appropriate alarm thresholds when events occur in the measured signal, ensure simplicity, versatility and practicality in managing the radio astronomy station. Fig. 22 shows the main console for displaying and controlling the program: it is a graphic window which displays the trend over time of the acquired radiometric signal, which includes the command buttons most frequently used for managing data acquisition, graphical representation of measurements and automatic recording. Versions of the program for the most popular PC platforms are available.

The window shown in Fig. 23 contains the commands necessary to set the instrument parameters. It is possible to select how often the measure must be updated according to the received samples. This is done by choosing the sampling period *SAMPLING*, a function which includes the calculation of the average value on the acquired samples, therefore another integration of the signal in addition to that established by the *INTEGRATOR* parameter: the program will update graph traces after acquiring the set number of samples, then it will calculate that number's average. The *CAL* button activates the automatic calibration of the baseline ("zero" reference) for the radiometric measurement. It is possible to save the values of the operating parameters in the internal memory of the receiver using the *MEM* command: so that every time the instrument is powered up, the optimal operating conditions are restored, chosen after appropriate calibration according to the characteristics of the receiving system and of the observed scenario.

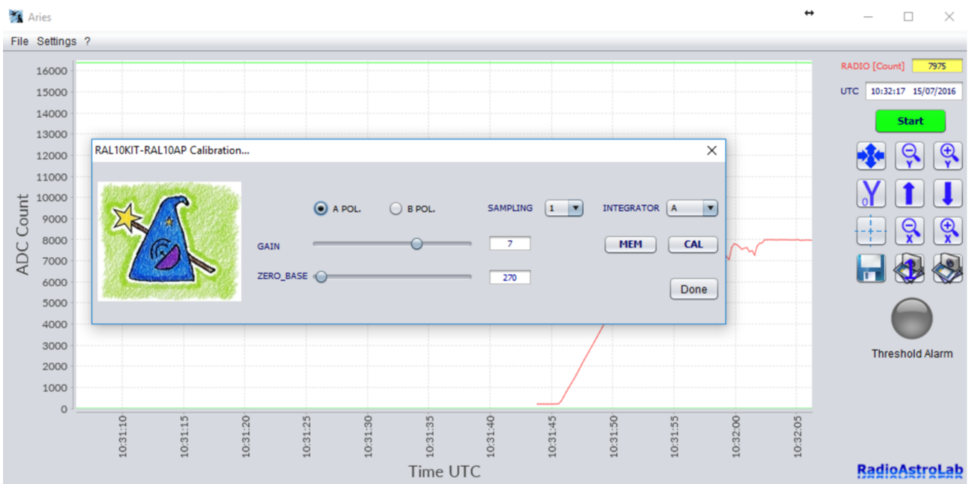


Fig. 23: Command window per setting receiver parameters.

Adjusts the resolution of the ordinates using the Y axis zoom buttons, then position the trace on the graph with the up or down arrow buttons so that it is completely visible in all its dynamic range (these are commands that allow the translation of the entire trace along the ordinate axis). Similarly, using the appropriate buttons it is possible to zoom in on the time axis (abscissa), also modifying the scrolling speed of the trace. The maximum speed that can be set is 60 seconds per screen: the trace will take one minute to cover the entire graphic window. In the program settings menu, it is possible to choose the time representation format (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 format or as an image using the dedicated data logging buttons. To check the progress of the signal received during a measurement session, the program offers the possibility of setting two control thresholds (upper and lower) which, if exceeded by the radiometric trace, will activate a visual alarm by colouring a red light and activating an audible alarm, if desired. The thresholds appear as two horizontal green lines in the graphics' window. Further details on the characteristics and functions of *ARIES*, as well as the updated versions of the program, can be found on the *RadioAstroLab s.r.l.* website. and on the user manual, which can be downloaded from:
http://www.radioastrolab.it/pdf/ARIES_Manuale_IT_11.pdf

12. Radio telescope calibration

Any instrument analyses a parameter according to a scale of specified units of measurement. This is also true for a radio telescope: when making absolute measurement, it is necessary to calibrate the instrument, then establish a calibration procedure to obtain a response consistent with an absolute scale of *brightness temperatures* (or flux units). Furthermore, the construction tolerances, the environmental conditions and the parametric variations of the active devices cause variations in the characteristics of the receiver and make each instrument unique in its response: it will be difficult to compare the measurements performed by different radio telescopes or those of the same system carried out at different times. By repeatedly observing a radio source, it is possible to find changes in the intensity of its emission: it is important to understand whether these fluctuations are due to real variations in the flow or to unwanted variations in the response of the instrument. For these reasons it would be desirable to refer to a universal measurement system. The calibration procedure of a radio telescope serves precisely to establish a relationship between the *brightness temperature* of the observed scenario (expressed in K) and a given quantity output from the instrument (expressed, as in our case, in arbitrary counting units of the ADC).

In this paragraph we will provide some suggestions to calibrate the measurement scale of an amateur radio telescope, in a simple and practical way, by observing easily available reference sources. As an example, the calibration of a system that uses the *RAL10AP* receiver and an offset satellite dish antenna for satellite reception in the 10-12 GHz band, similar to the one shown in Fig. 13, is described. The technique is simple: even if approximate, it is suitable for the needs of an amateur instrument, which 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 acquired by the internal analogue-digital converter (ADC), it is possible to calibrate the instrument by measuring two different power levels of the received radiation: first observe a *hot target* (object at room temperature), then a *cold target* (such as, for example, the sky at the zenith) by calibrating the antenna temperature directly in K. In practice:

- Measurement of the *cold target*: the antenna is oriented towards the sky at the zenith, on a clear and dry day. If the radiative contributions from the Sun, the Moon and other sources are absent, the brightness temperature T_{sky} of the sky at the zenith can be estimated using the procedure described in Appendix A. Neglecting the noise contribution due to the radiation picked up by the secondary lobes of the antenna, the value T_{sky} =6.8 K is used.

- Measurement of the hot target: the antenna is oriented towards the ground so as to cover its entire field of view, at a distance enough to consider the far field condition satisfied. If the physical temperature of the ground (measurable with a thermometer) is T_{soil} and its microwave emissivity is η=0.95 (an estimated average value), its brightness temperature will be:

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

Since the emissivity value is close to 1, the sky radiation reflected by the ground towards the radiometer has been ignored.

If the responses of the instrument when measuring targets with different brightness temperatures T_{b_soil} and T_{sky} are, respectively, $count_{soil}$ and $count_{sky}$, one can express the equivalent antenna temperature T_a in function of the corresponding radiometric response *count* as:

$$T_a(count) = T_{b\_soil} + \left(T_{b\_soil} - T_{sky}\right) \cdot \frac{count - count_{soil}}{count_{soil} - count_{sky}}$$

Equation of a straight line on a plane {*count*, T_a}.

The temperature T_a measured by the radiometer will generally depend on the directive characteristics of the antenna used (shape of its reception diagram) and will be different from the brightness temperature of the observed scenario, given that the antenna operates a convolution between the shape of its reception diagram and the brightness profile of the source. The calibration line just found converts the radiometric measurements expressed in arbitrary acquisition units of the ADC into an absolute temperature scale, then determines the calibration characteristic of the instrument.

This simple procedure is approximate, although adequate for our needs and provides an acceptable estimate of the dynamics of the instrument's measurement scale in K. Its accuracy depends on many instrumental and environmental factors: the estimates on the brightness temperature of the T_{sky} sky and on the emissivity η of the ground (the *hot target*), and the constancy of the radiometer parameters (stability, especially with temperature) have a great influence and the linearity of its applied power/detected voltage characteristic. Fig. 24 shows the recordings of the response of a radio telescope using the *RAL10AP* receiver when the antenna is oriented towards the ground (a large, freshly ploughed piece of uniform land has been chosen, for which we have estimated η≈0.95) and when the antenna "sees" the clear sky at the zenith. After measuring the physical temperature of the ground, the responses of the radiometer to the two hot and cold targets were used to calculate, using the previous formula, the instrument calibration line.

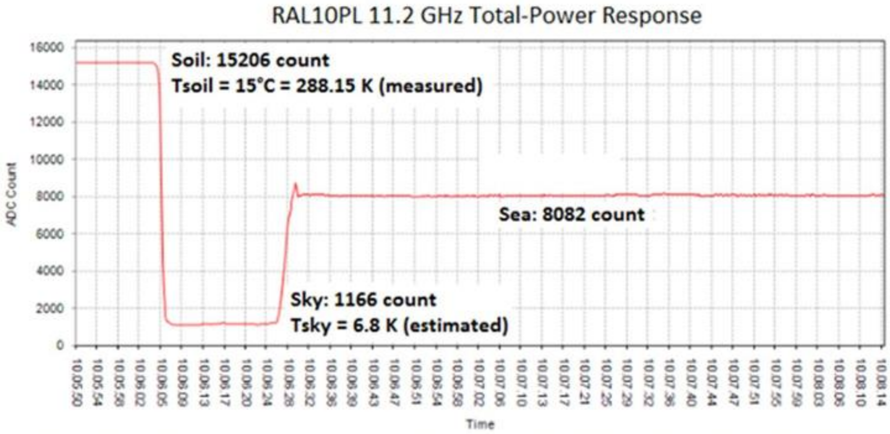


Fig. 24: Measures of the ground and the sky at the zenith for radio telescope calibration (*RAL10AP* receiver).

13. 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 10-12 GHz frequency band, considers the contribution of the antenna noise due to natural atmospheric disturbances (hydrometeors, lightning, thunderstorm electrical discharges) and artificial atmospheric disturbances to be negligible. Therefore, it is assumed that the only source of radiation from the atmosphere is the noise due to the atmospheric absorption of the constituent gases and molecules, expressed as the radiant temperature of the atmosphere $T_{atm}(f,\theta)$, which depends on the frequency f and on the elevation angle θ of the antenna with respect to the horizon. For its evaluation, the graph in Fig. 25 was used, 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 the radiative transfer in the Rayleigh-Jeans approximation, excluding the noise contributions due to the cosmic microwave background (T_{CMB} =2.725 K), the emission of the galaxy, other cosmic sources such as the Sun and the Moon and the ground captured by sidelobes of the antenna. By extrapolating the data from the graph, in the 10-12 GHz frequency band, a table of values is obtained and by interpolating we are able to calculate the contribution of noise from the atmosphere due to absorption phenomena (U.S. Standard Atmosphere model, 1976), function only of the elevation angle of the antenna with respect to the horizon (Fig. 26).

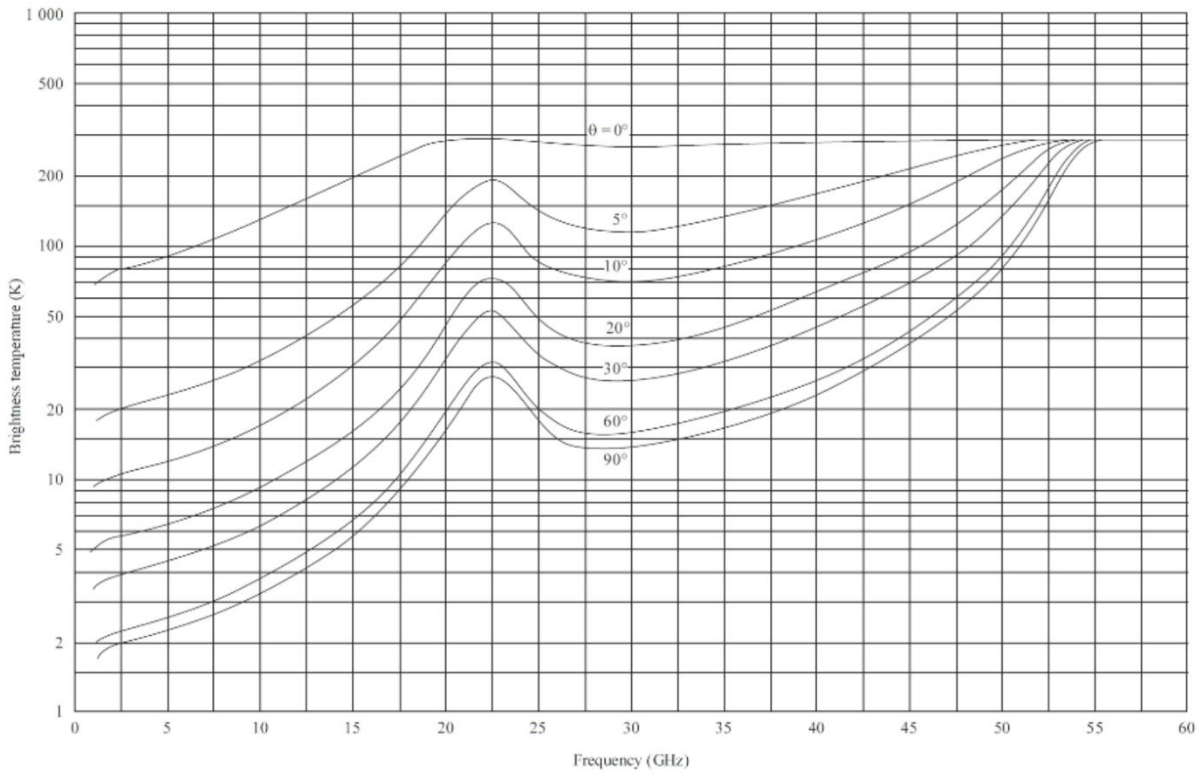


Fig. 25: Simulated brightness temperature of the atmosphere (Recomm. ITU-R P.372-12 (07/2015) Radio Noise).

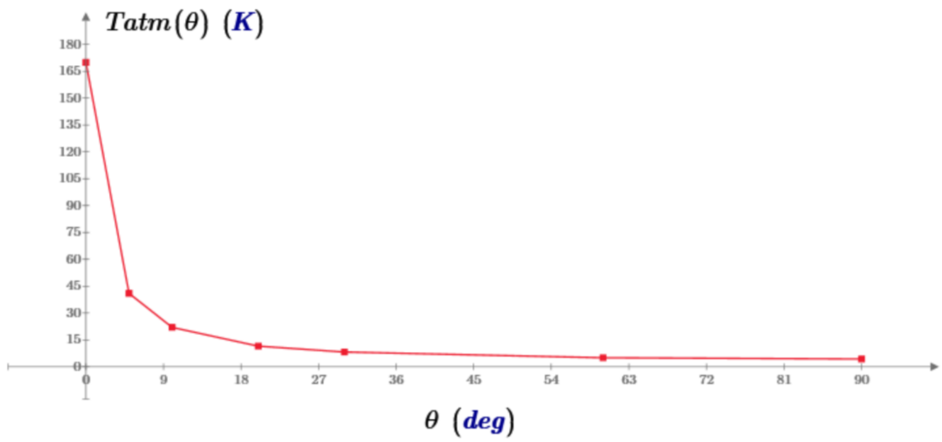


Fig. 26: Brightness temperature of the atmosphere at 10-12 GHz, in function of the elevation angle of the antenna obtained by interpoling the obtained values by sampling the previous graph.

By adding the noise contribution of the cosmic microwave background TCMB to the value of the brightness temperature of the atmosphere at the zenith (θ=90°) obtained from the previous graph, a brightness temperature of the sky at the zenith equal to $T_{sky}(90°)$ =7.025 K is detected. This value can be used in the radiometer calibration procedure as the temperature of the *cold target*. If we also want to consider the radiation coming from the ground, captured through the secondary lobes of the antenna, we can add a contribution of the order of 3-5 K, depending on the characteristics of the antenna and the maximum level of its secondary lobes. This approximation is generally acceptable for amateur radio telescopes oriented towards the zenith sky, sufficiently distant from obstacles or buildings.

For comparison, it is useful to attempt an alternative estimate of the zenith sky brightness temperature using other data. The graph in Fig. 27 calculates the brightness temperature of the atmosphere using the radiative transfer equation (in the Rayleigh-Jeans approximation), including the noise contributions due to the cosmic background and the galaxy.

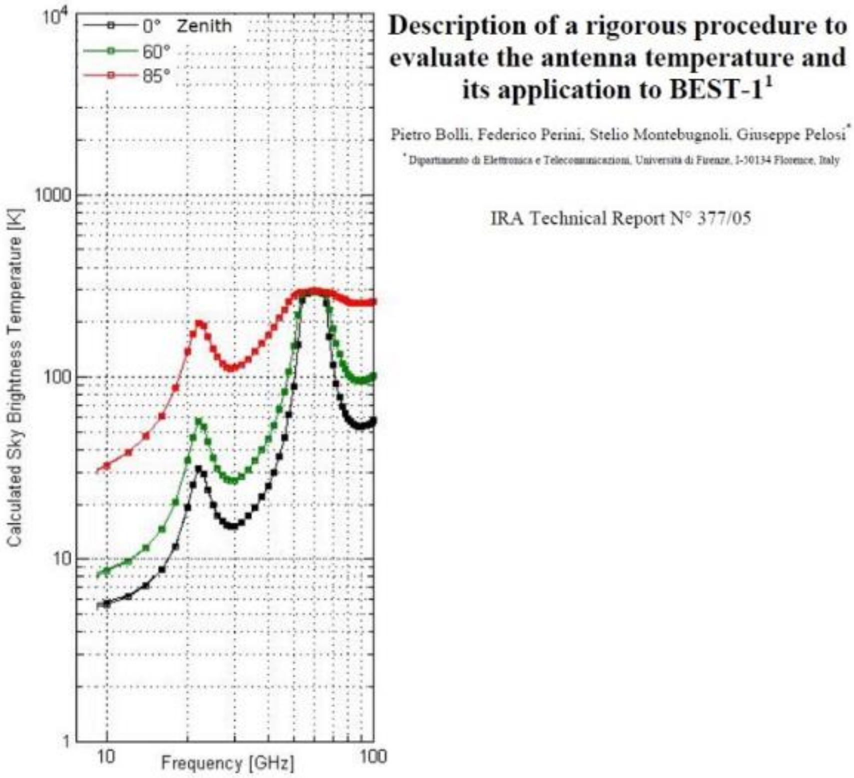


Fig. 27: Brightness temperature of the atmosphere (IRA Technical Report N. 377/05).

By extrapolating the data for the 10-12 GHz band it can be seen how, when the radiometer antenna is oriented towards the sky at the zenith, a brightness temperature of the order of $T_{sky}(90°)$=7 K is measured, in agreement with the previous evaluation.