Radio Meteors

Flavio Falcinelli, *RadioAstroLab s.r.l. - Strada della Marina 9/6 Senigallia (AN), Italy - http://www.radioastrolab.it*

A very interesting activity is the radio observation of astronomical phenomena that influence the Earth's ionosphere. In this paper we describe an amateur observation technique that uses a bi-static radar system to record the radio reflections produced by the ionized trails that are formed, at about 100 km high, when very fast objects from outer space consume entering the Earth's atmosphere.

Radio observation of meteoric events

During its motion of revolution around the Sun the Earth crosses the orbit of a very large number of bodies, called *meteoroids*, with a mass between about 10^{-15} g and 10^{15} Kg and speed of entry into the atmosphere varying between about 11 Km/s and over 70 Km/s.

The progenitors bodies of the meteoroids are the comets, whose cores consist of ice and dust that liberate gas and debris during their approach to the Sun, forming the crown and the characteristic tail, and the asteroids, rocky and / or metallic bodies mainly confined in the Main Asteroidal Belt, between the orbits of Mars and Jupiter. Unlike comets, asteroids contain no volatile elements and it is the reciprocal collision that expel the fragments in space with relatively low speeds: debris tend to remain within orbits similar to those of the parent body, forming a *meteor shower*.

For perspective reasons, to an observer it will seem that the meteors of the same shower radiate from a small region of the sky, called *meteoric radiant* which is named after the constellation or the star nearest to the radiant. About 150 meteor showers are known, distributed throughout the year: the most important are listed in Figure 1.

Sciame	Periodo di attività	Data max	Coordinate radiante		Velocità (km/s)	ZHR max	Corpo progenitore
			AR	DEC			
Quadrantidi	01/01 – 05/01	03/01	15h 20m	+49°	41	120	(196256) 2003 EH_1
Liridi	15/04 – 28/04	22/04	18h 04m	+34°	49	15	C/1861 G1 Thatcher
Eta Aquaridi	19/04 – 28/05	06/05	22h 32m	-01°	66	60	1P/Halley
Arietidi	22/05 – 02/07	07/06	02h 56m	+24°	38	54	1566 Icarus
Beta Tauridi	05/06 – 18/07	29/06	05h 18m	+21°	n/a	25	2P/Encke
Sud Delta Aquaridi	12/07 – 19/08	28/07	22h 36m	-16°	41	20	?
Perseidi	17/07 – 24/08	12/08	03h 04m	+58°	59	90	109P/Swift-Tuttle
Draconidi	06/10 – 10/10	08/10	17h 28m	+54°	20	Var.	21P/Giacobini-Zinner
Orionidi	02/10 – 07/11	21/10	06h 20m	+16°	66	20	1P/Halley
Leonidi	14/11 – 21/11	17/11	10h 12m	+22°	71	Var.	55P/Tempel-Tuttle
Alpha Monocerontidi	15/11 – 25/11	21/11	07h 20m	+03°	60	Var.	?
Geminidi	07/12 – 17/12	14/12	07h 28m	+33°	35	120	3200 Phaethon
Ursidi	17/12 – 26/12	22/12	14h 28m	+76°	33	10	8P/Tuttle

Figura 1: *List of the main meteor showers [2].*

Our planet is then subjected to a continuous "bombing": the effects would be disastrous if the atmosphere didn't exercise a screen action dissipating their kinetic energy into electromagnetic radiation (heat, light and ionization).

The term *meteor* should only designate all the phenomena resulted from a meteoroid, but it is customary to extend its meaning even to the body itself. We call *meteorites* the larger objects (with a mass greater than 10 kg), which, although consumed by the friction with the atmosphere, are able to reach the surface where they also produce craters of considerable proportions. At the opposite extreme we can find the *micrometeorites*, very small particles (mass below 10^{-7} g) that dissipates all their kinetic energy by irradiation and fall slowly, reaching the surface by gravity.

The most interesting phenomena for our study are related to meteors, bodies with mass between 10^{-7} g and 10^4 g which produce significant ionization effects in the upper part of the atmosphere (altitudes between 80 km and 120 km). These objects are all the more numerous as smaller are their size and, with a good approximation, it can be estimated that the meteor stream with masses greater than a given value is inversely proportional to that value. Each day on average about ten million meteors with greater mass than or equal to one hundredth of a gram and four billion bodies with mass greater than or equal to one ten-thousandth of a gram enter the Earth's atmosphere . As you will see experimentally (figure 16), the meteor stream that strikes the Earth is characterized by large diurnal variation, with a maximum around the early morning hours and a minimum around 6 p.m.: the relationship between the two extremes is of the order of 5.

The ionization phenomenon generated by meteor impacts on the physical conditions of the lower regions of the ionosphere and is very important for the propagation of radio waves at large distances: to study the electromagnetic radiation and the effects caused by the column of electrons formed by the passage of a meteoroid represents the purpose of our projects.

When entering the earth's atmosphere with 70-100 Km/s speeds, an body impacts with the air molecules freeing, at every collision, thermal energy of the order of 100 eV: the succession of impacts considerably heats the object that merges and evaporates on the surface, gradually losing mass (ablation process). The atoms of the meteoroid, released by ablation, collide with molecules and atoms of the air releasing a certain amount of energy that causes electromagnetic radiation, light excitation and ionization of the atoms expelled, in addition to a local increase of the air temperature. The ionized track, while forming, generates a cylindrical structure with a radius of about 10 cm and a bulk density of free electrons much higher than that of the surrounding air: after a certain time begins a process of diffusion (and recombination) of free charges that cause a rapid decay of the volumetric charge density (number of free electrons contained in a cubic meter of the trace), until its complete dissolution.

The long and thin plasma columns of short duration generated by the ionization of a meteoric event are able to reflect radio waves emitted by a *radar* operating in the VHF band (30-300 MHz).

This term (*Radio Detection And Ranging*) identifies an electronic system that observes distant objects using reflection or dispersion(*scattering*) of radio waves emitted by a transmitter that "illuminates" the target. The VHF radar is, therefore, a powerful means of investigation for the study of solar system bodies.

The radars dedicated to the study of meteors and interplanetary matter that interacts with the Earth's atmosphere are called *meteoric radars* and the most popular are of bi-static type: the transmitter and the receiver are positioned away from each other, so that the curvature of the earth prevents the receiver to directly pick up the signals from the transmitter (figure 2). Only when the meteoric track reflects or diffuses obliquely (*forward scattering*) the radio waves hitting it, the echo reaches the receiver and produces a radar track. For a bi-static radar, the volume of atmosphere from which the radio reflections come is given by the intersection of the reception lobe of the transmitter with the one of the receiver.

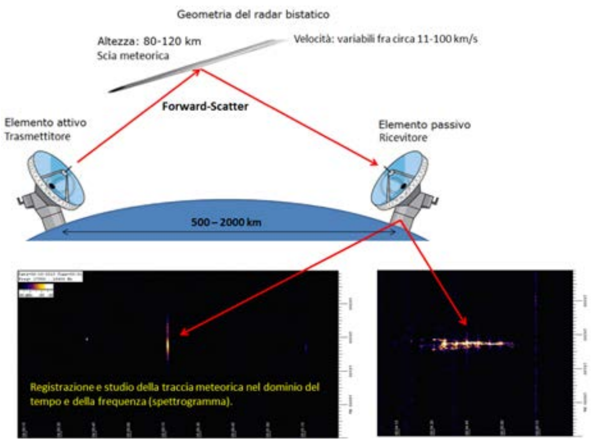

Figura 2: *Geometry of the meteoric bi-static radar (elaborated by [2]).*

This technique, called *Radio Meteor Scatter*, has many advantages over other methods of observation: it is continuously operating at any hour of the day, is not sensitive to weather conditions, it covers large areas of the sky and is capable of detecting very small meteors (mass of the order of micrograms). The system is suitable not only for the monitoring of meteoric traces and space debris, but also of many other atmospheric phenomena capable of dispersing electromagnetic energy in the VHF band (such as, for example, lightnings), and is easily implemented with an antenna, a good radio receiver and a computer.

We can then study this phenomenon at amateur level by installing the passive part (the receiving one) of a bi-static radar in order to exploit a powerful commercial or military radio transmitter as the active part.

One of these, particularly suited for the purpose, is the French radar *GRAVES* (Grand Réseau Adapté à la Veille Spatiale), a space surveillance system that detects artificial satellites and debris orbiting around the Earth at heights between 400 km and 1000 km, calculate their orbits, and classifies them. GRAVES is a bi-static radar: the transmitting system is located about 35 km east of Dijon and the receiving part approximately 360 Km to the south. The transmitter (figure 3), operating at the frequency of 143.050 MHz, consists of 4 arrays of panel antennas (phased array) mechanically fixed in azimuth (distributed so as to cover the south corner 90-270 degrees with an angular spacing of 45 degrees between one panel and the other) and in elevation (with angle of about 30 degrees and opening of the bundle of 20- 25 degrees). The carrier of the radio signal is transmitted simultaneously in 4 different directions in the sky, equally spaced, with a radio power of about 10 kW per panel.

Figura 3: *Two of the four panel antennas of the radar transmitter GRAVES operating at 143.050 MHz (Observatoire de Paris, Division Surveillance Espace).*

Figura 4: *Distance TX-RX of the bi-static radar.*

To observe and record the reflected radio signals from ionized meteor trails, tune the receiver to the frequency of the radar transmitter GRAVES that constantly "illuminates" a large portion of the sky. Only when the meteoric track reflects or diffuses obliquely the incident radio waves generated by the transmitter, these can reach the receiver, and produce a radar echo. The phenomenon (with a typical duration from fractions of a second to a few seconds) is studied by analyzing the evolution in time of the spectrum associated with radio reflection of ionized meteor trail (spectrogram), using suitable programs available for free on the web. Measuring the received signal strength and its doppler frequency shift, you obtain important information on the source movement.

This system is conceptually simple and economical, within everyone's reach: it is sufficient to have a good VHF receiver operating on the same frequency of the transmitter, an antenna and a PC equipped with an appropriate software.

You can choose several transmitters as " illuminators " of the sky: commercial FM broadcast stations operating in the range 88-108 MHz (it is not always easy to do, since the band crowding), analog TV broadcasters (unfortunately there are few left, all in Eastern Europe), or dedicated transmitters as that of the French radar GRAVES operating at 143,050 MHz, used to control space debris in orbit around the Earth and chosen for our radio meteors observation projects.

It's very important that the transmitter guarantees a continuous service and is at a distance, from the receiving station, comprised between 500 and 2000 km away. Furthermore, it is desirable that the power of the signal transmitted is stable, at non-modulated continuous wave (CW) and that the transmitting antenna beam " illuminates " always the same area of the sky, without spatial variations.

The GRAVES radar transmitter does not meet fully all the requirements, since the transmitting antenna beam does not " illuminate " always the same area of the sky, but will periodically scan producing gray areas where eventual meteoric traces may not be detected (figure 5). Despite this, the French transmitter seems one of the most reliable in terms of continuity of operation and purity of the emitted radiation and is positioned at the right distance from our receiving stations.

The following paragraphs describe two projects that implement a bi-static radar using GRAVES transmitter to observe objects that pass in the sky at an altitude of about 100 km. The distance of the transmitter from our receiving stations is about 725 km as the crow flies (figure 4), so the carrier of the transmitter at 143,050 MHz is not receivable, normally, by direct wave.

The study of radio reflections will take place in the frequency domain, using spectrograms. These radio-echoes (which last from fractions of a second to a few seconds) are manifested as sudden increases in the level of the signal received and analyzed by measuring their intensity and their Doppler shift in frequency, obtaining important information on the motion of the source that causes the scattering.

The experiments will have the following purposes:

- Check the feasibility and functionality of two different stations that perform passive elements of the bi-static radar in VHF based on the active element GRAVES.
- Use a technology commonly available to radio amateurs for the construction of the stations.
- Learn and deepen the technical and physical principles that regulate the operation of the system (*meteor scatter* technique, VHF radio propagation effects, characterization and analysis of events in the frequency domain).
- Exploiting the activity of the most important meteor showers to check the operation of the instruments and schedule public demonstrations alongside the optic ones.
- Compare our observations with those of other enthusiasts to test and study possible correlations.
- Use the base station as a remote element connected to an amateur network of observers working in continuity 24 hours a day.

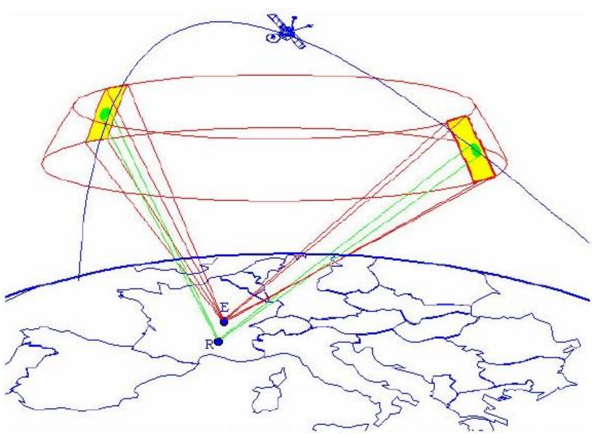

Figura 5: *Sky region "illuminated" by the radar GRAVES.*

The first part of the analysis will be useful to collect and catalog a high and differentiated amount of " spectral signatures " of the reflections with the aim of highlighting the geometry and the evolution of each phenomenon, well represented in the spectrogram of the event.

It will not be difficult, with time, to prepare a catalog of detailed spectral images that describe the type and the time evolution of meteoric echoes. In parallel, you can implement algorithms aimed at counting the long-term events and evaluate statistics on their annual occurrence. This can be simplified by using suitable software, developed by enthusiasts, available for free on the web.

Two prototypes of receiving stations were built, that meet different needs: a fixed station, operating continuously 24 hours a day, remotely controllable and meant for the monitoring and the continuous recording of the events, and a mobile station used " on the field " in public demonstrations, in parallel to the traditional visual observations of " falling stars " during the occurrence of the major meteor showers.

The fixed station *RALmet*

The experimental fixed station *RALmet*, operating at the frequency of 143.050 MHz, is optimized for the reception of the meteoric echoes produced by the French radar GRAVES. The receiver and antenna were built for this purpose.

The system operates continuously, 24 hours a day, recording spectrograms received at regular time intervals, downloaded daily from the station PC and subsequently analyzed. Counts of events, spectral analysis and statistical analysis are being performed.

The receiver can be a good VHF receiver for radio amateurs coupled to a commercial antenna [2] (on the web there are excellent examples of amateur stations), or designed and built specifically for this application, as in our case. We will provide some information about the technical features of our receiver and antenna used, useful to understand the requirements of the receiving station, relevant to conduct serious research in this area. Obviously this is one of many possible proposals, not the best, but represents a configuration that, after some optimizations, has perfectly met the expectations.

In fact, much care has been devoted to the construction of a dedicated receiver that had to be very stable in frequency, equipped with a " robust " and efficient in-band filter system (to minimize the effects caused by interference), devoid of any automatic control of frequency and gain, centered on the frequency of 143,050 MHz of French radar transmitter GRAVES.

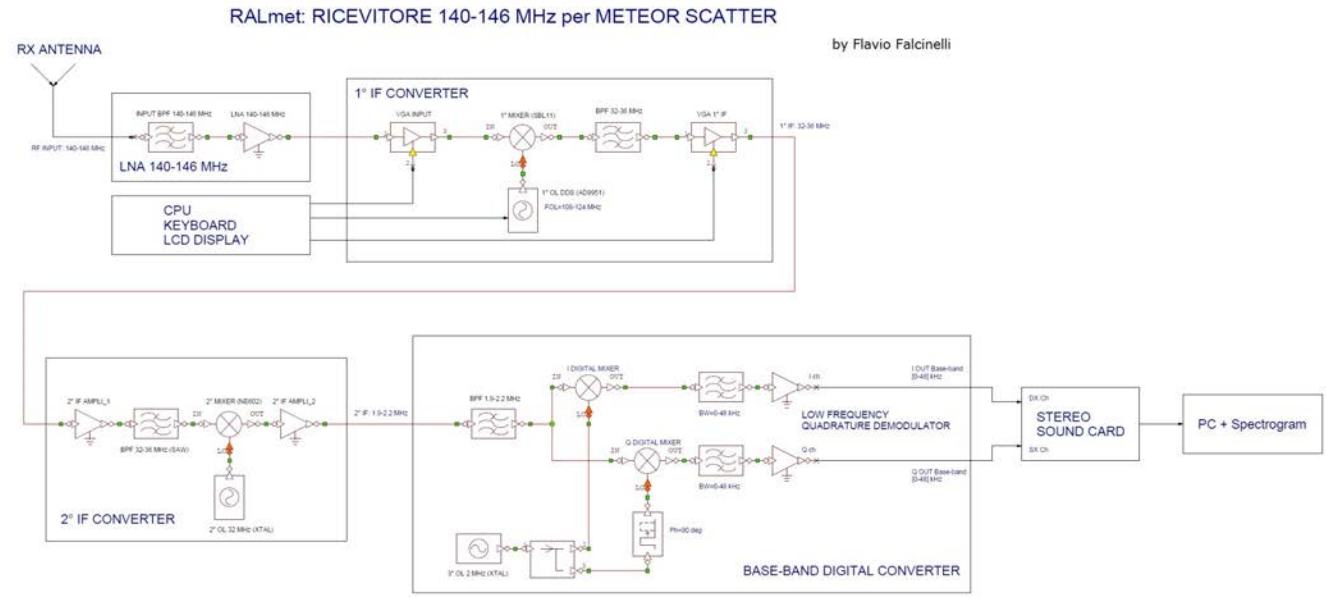

Figura 6: *Structure of the receiver used in the fixed station* RALmet.

The present antenna is a simple rigid dipole " cut " on the frequency of 143,050 MHz, equipped with a balun (a device which adapts the balanced impedance of the dipole to the unbalanced one of the coaxial cable that carries the signal to the receiver), installed on the roof of a building and oriented with its reception lobe (perpendicular to the dipole elements) in the direction of the transmitter. This solution has been adopted as a classic " makeshift " remedy after a storm that damaged the originally planned antenna, consisting of two crossed yagi 3 elements oriented at the Zenith.

What initially was to be a fallback and temporary configuration has become an lasting and technically interesting option. The large reception lobe of the dipole, in fact, is a great advantage in this application: if suitably oriented with respect to the transmitter and positioned at a proper height from the ground, it allows the reception of meteoric echoes without too many restrictions from the orientation point of view and saferly against the most violent weather events. When the dipole is combined with a suitable receiver with optimized bandwidth (only the one needed) and followed by a properly configured software for the acquisition of the spectrograms such as *Spectrum Lab* (excellent job by Wolfgang Büscher, DL4YHF downloadable for free from the web), the results are great, at least for the goals of our project. So much that we decided, contrary to the initial intention, to make this configuration permanent.

Despite the reduced dipole sensitivity, we could see how a sufficient distance from the transmitter, such as to prevent direct reception of its carrier (along with all the spurious radio echoes, including those caused by air traffic) and an optimized antenna-receiver coupling are crucial to discriminate, without errors, the tracks caused by the meteors.

Between the dipole and the receiver a pre-amplifier was inserted, with a pass-band filter 130-160 MHz specially built.

The receiver is at triple frequency conversion (the structure is shown in Figure 6), with an input band 140-146 MHz translated to the base-band 0-48 kHz and an output with signals in phase (I) and quadrature (Q), indispensable to implement and manage via software the techniques of the image frequency rejection. The receiver does not perform demodulation and output signals are sent to the stereo inputs of an external sound card (24 bit, 96 kHz sample rate), dedicated to the acquisition of signals in base-band, connected to the computer (PC) through a USB port.

The system is very stable in frequency and uses a main local oscillator in DDS technology programmable by a processor for the setting of the reception frequency. A prototype is shown in Figure 8.

By choice, we avoided any automatic system for the counting of meteoric events: after many tests, we configured the program *Spectrum Lab* for the acquisition of both base-band channels I Q of the receiver (the one in phase and the one in quadrature) with rejection of the frequency image, enhancing the resolution in the spectrogram frequency and setting a periodic and automatic data logging at the rate of a spectrogram every 3 minutes.

The use of the *TeamViever* software (this too is

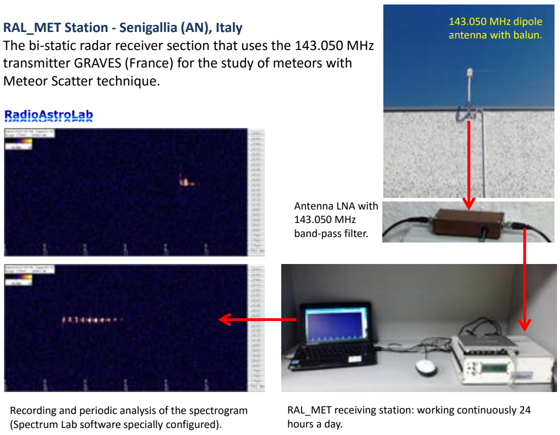

Figura 7: *Fixed station* RALmet.

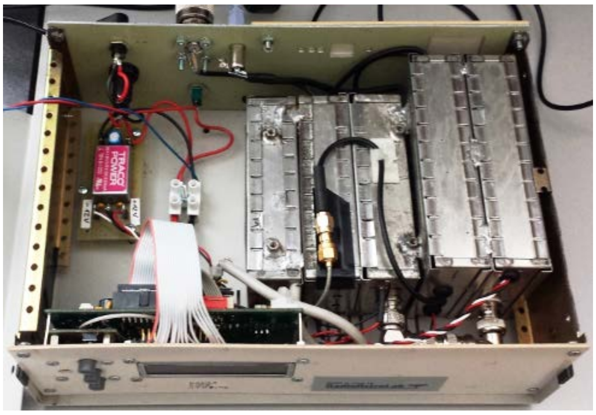

Figura 8: *Prototype of the receiver built for the fixed station* RALmet.

available for free on the Internet for personal use) enables the remote control of the acquisition PC comfortably from home, with the ability to download every day the spectrograms recorded.

The following data analysis is visual: you need to patiently check the individual records to detect spectral "signatures" of meteoric events to count and classify them. This approach, certainly more laborious than the automatic systems via dedicated softwares, is very accurate and reliable, since it minimizes the counting of false events, even if it requires an initial period of "running-in" to gain experience.

Interesting examples of the spectrograms recorded by the fixed station *RALmet* are shown in Figures 9, 10, 11, 12 e 13, where you can see complex structures that are often difficult to interpret. In many cases they are ionised parts that occur with different frequency (ie different group velocity) starting at a given instant, disappearing and reappearing later at the same frequency. The evolution of these traces is, probably, the combination of a series of processes that interact: distinct parts of the meteor may, for example, be the result of successive ionization steps,

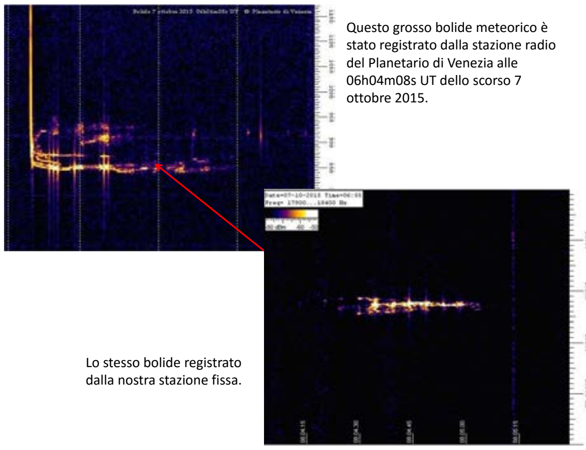

Figura 9: *Meteoric fireball recorded at 06h04m08s UT on the last 7 October 2015.*

carried by strong winds aloft with different paths.

As you can see, the tracks of the reflections are displayed with spectrograms, images that represent the evolution of the phenomenon in the frequency domain: the horizontal axis represents time, the vertical axis the reception frequency, expressed in Hz, the signal in baseband on the output of the receiver. The intensity of the phenomenon (expressed in a scale of relative signal powers) is displayed according to a scale of false colors (represented in the legend shown in the upper left of each spectrogram) where the light colors indicate higher power of the received signal. This type of representation is very convenient and effective for the analysis, since it displays "at a glance" the spectral evolution of meteoric tracks: with a little practice the special features of the phenomenon are easily distinguishable (the so-called "spectral signatures"), as weel as some parameters such as the relative speed of the track, with respect to the observer, deduced from the signal frequency Doppler shifts.

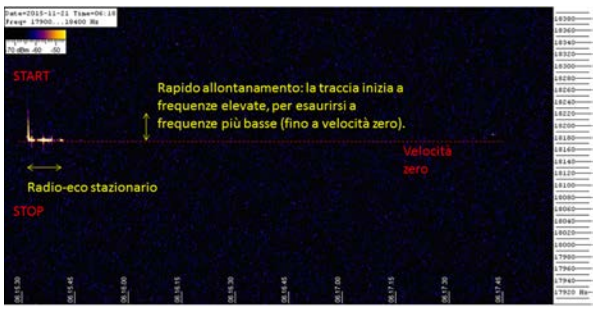

Figura 10: *The peculiar "L" shape of this track indicates a meteor that, while rapidly moving away from the observer (vertical portion), stops (zero relative speed) and generates an ionization level sufficient to maintain a stationary echo for a few seconds.*

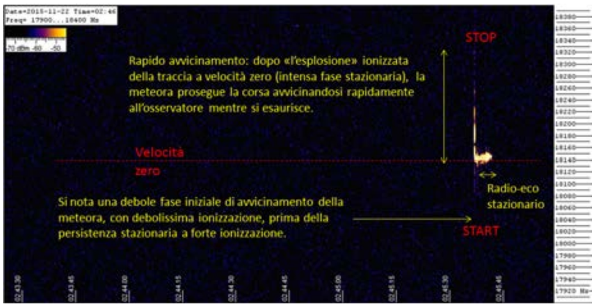

Figura 11: *Meteor with behavior similar to the previous one, but with opposite movement with respect to the observer.*

Figura 12: *Multiple and complex setup of a ionized track, similar to those seen previously, with very weak vertical section and separation of the intense stationary ionization probably due to winds aloft.*

La figura 14 mostra il conteggio di eventi "radio-meteorici" registrati con continuità giornaliera dalla stazione fissa *RALmet* nel periodo novembre 2015 - giugno 2016. Si notano i principali sciami meteorici del periodo: durante i previsti giorni di massimo, il numero di eventi registrati aumenta rispetto al valore di fondo dovuto al flusso sporadico. Degno di nota è il sensibile incremento di radio-bolidi registrati durante il mese di maggio (figura 15).

The Figure 16 shows the diurnal variation of the radio-meteor numbers recorded by our station: as expected, there is a peak of activity between midnight and dawn. During the night, in fact, the observer located in the terrestrial part of the hemisphere in front motion with respect to the meteor stream, records a greater relative speed of meteor impact with the atmosphere that increases the ionization rate by ablation (thus a greater number of radio-echoes recorded by the bi-static radar). The opposite occurs during the afternoon, when the observer is located in the terrestrial hemisphere opposite to the direction of impact of the meteor flow.

The experimentation goes on: the main purpose of the fixed station *RALmet* is to to catalog the spectral "signatures" of considerable meteoric radio-echoes,

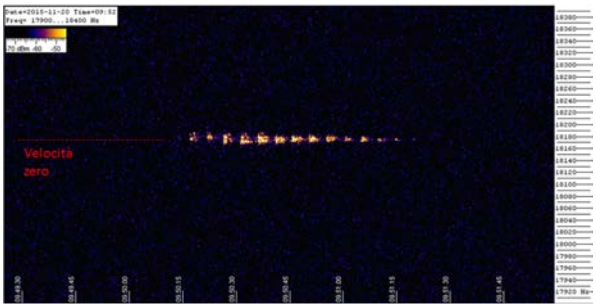

Figura 13: *This is the most significant event registered in November 2015. It is a stationary ionized track (i.e. at zero speed) of the duration of about 1 minute, produced by a large-size meteor.*

count the number of events per day for long periods of time (for example, one year) highlighting the major meteor showers of the year and changes in them during a period of few years, counting the number of fireballs or, in general, of remarkable events that occur every month. It is an ongoing observation with long-term goals. The system records a large amount of data to be analyzed, cataloged and counted: we're studying an automatic system to handle the counting and the production of alarms when significant events are detected.

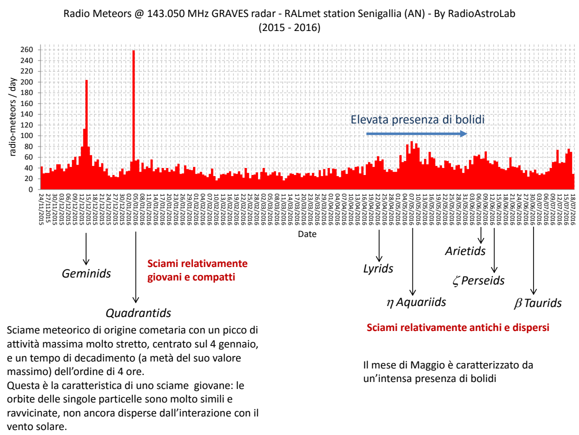

Figura 14: *Count of "radio-meteoric" events recorded by the fixed station* RALmet *with daily continuity in the period November 2015 - June 2016.*

"The mobile station for the "fieldwork" observations

In addition to the fixed station, another mobile receiving station was built (figure 17), always tuned on 143,050 MHz frequency and occasionally activated

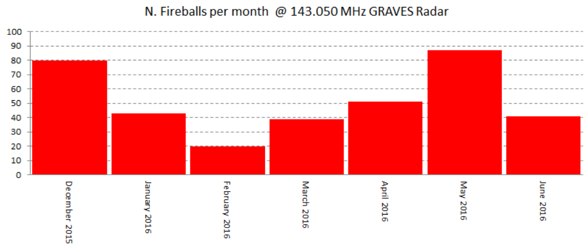

Figura 15: *Number of " radio fireballs " observed each month.*

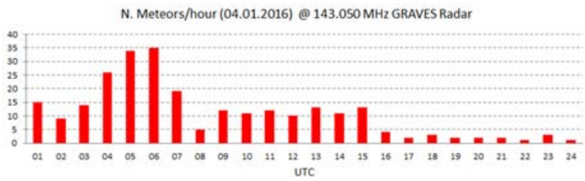

Figura 16: *Diurnal variation of radio-meteor number.*

for demonstration purposes during the periods of major meteor showers.

The receiving system uses a 3 elements yagi antenna specially built, set on the 143,050 MHz frequency and positioned on the roof of a car through an easily manageable and adjustable support. We used this type of antenna because it is simple and economical to build, characterized by an appropriate gain and a receiving lobe not too narrow to not excessively limit the field of view.

The receiver is of SDR type, that receives the supply voltage directly from the USB port of a laptop used for the acquisition. Thanks to its flexibility and compactness, this equipment has been successfully used for "fieldwork" public demonstrations, parallel to optical observations when the major meteor showers of the year occur: it is interesting and educationally useful to show the evolution the meteoric phenomenon in the radio band in parallel to the traditional visual observations, capturing the observer's attention on the dynamics of the trace produced by a meteor, enhanced by the ability to display real-time spectrogram. In fact, the purpose of these experiments is to show the shape and the evolution of the ionized track produced by the impact of meteorites with the atmosphere.

The following images show some observations made during the Perseids shower (August 2015). The comparisons between the recordings of the same shower events carried out by independent observers positioned in geographic locations far from each other and equipped with various equipment are particularly interesting. Despite the time lags due to the lack of synchronization of the computers, there are clear correlations between the recorded events and you can easily recognize their spectral "signatures".

The analysis of these recordings suggests interesting study options that can be developed by activating a coordinated (and accurately synchronized) monitoring of the meteoric events between distant stations.

The fugure 22 shows an example of a possible correlation between visual observation (we didn't photograph the event but just wrote down some distinctive details during its occurrence) and the corresponding radio recording of the same phenomenon.

Figura 17: *Mobile station for the observation of radio meteors.*

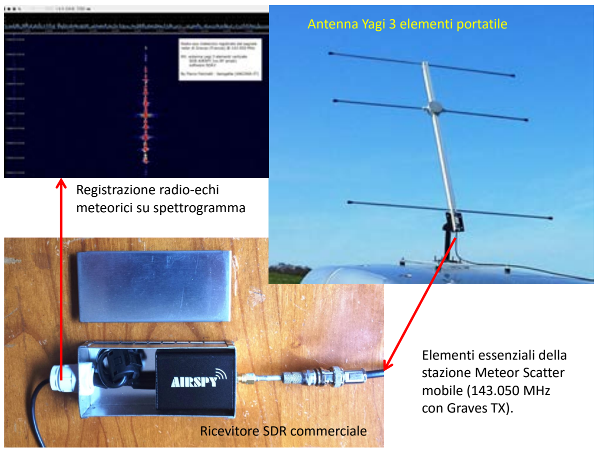

Figura 18: *Details of the mobile station for Meteor Scatter.*

Riferimenti bibliografici

[1] F. Verniani. Il fenomeno meteorico: aspetti teorici ed applicazioni. *Radio Rivista, n. 9, Settembre 1972.*

[2] G. Pupillo, C. Bortolotti, M. Roma. Sistema a uso didattico per la ricezione di echi radar meteorici. *Technical Report IRA 483/14.*

[3] J. M. Wislez Forward scattering of radio waves off meteor trails. *Proceedings IMC, Brandemburg 1995.*

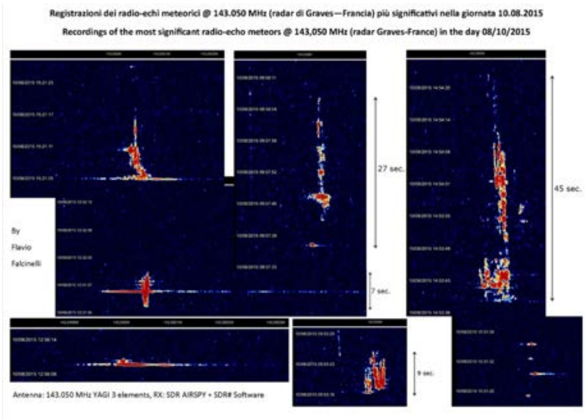

Figura 19: *Significant radio-echoes registered on 10 August 2015 (Perseids).*

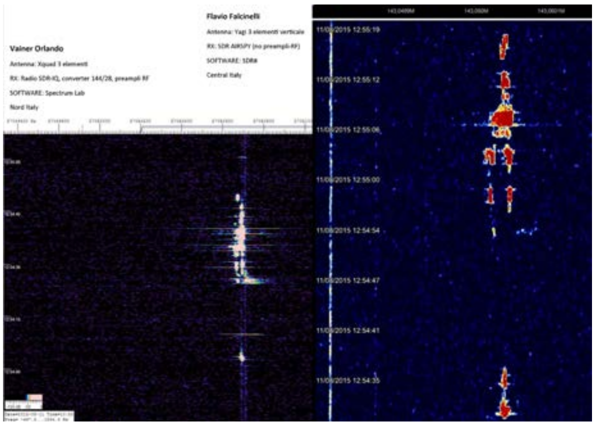

Figura 20: *Event recorded by two independent stations (Perseids 2015).*

[4] I. Yrjola, P. Jenniskens Meteor stream activity: a survey of annual meteor activity by means of forward meteor scattering. *Astronomy and Astrophisics, 1998.*

[5] D. Morgan Detection and Analysis of Meteors by RADAR (Using the GRAVES space surveillance transmitter). *Com. privata.*

[6] T. Pintér, J. Kákona, M. Kákona, L. Křivský Radio Meteor Scattering with Software Defined Radio based on Open Hardware. *Com privata.*

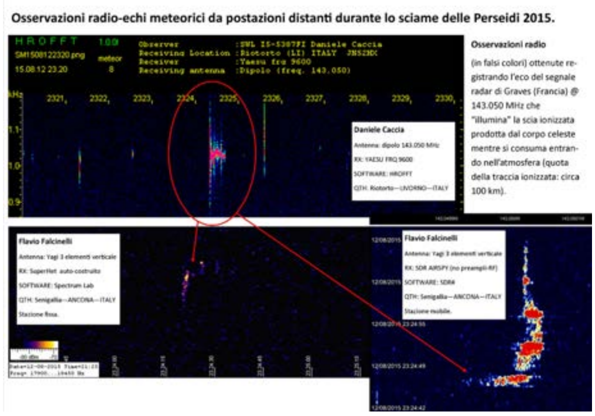

Figura 21: *Event recorded by three independent stations (Perseids 2015).*

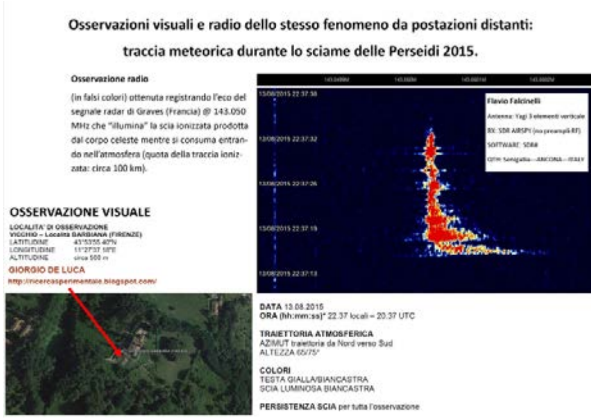

Figura 22: *Possible correlations between the visual observation of meteors (Perseids 2015) carried out by Giorgio De Luca in Barbiana (FI) and radio observations made by the mobile station in Senigallia (AN).*