What CARMELO can observe

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The CARMELO (Cheap Amateur Radio Meteor Echoes LOgger) network made of cheap and homemade receivers created so far, although small, shows the potential of this innovative project in the field of meteor observation using the meteor scatter method.
The system measures and represents waveforms and frequency of every single meteor echo received in a way never seen before by any amateur observer.
This article describes some types of waveforms displayed by the system and analyses, if present, the head echo, highlighting its Doppler shift. A possible methodology for calculating the speed of the meteor as a function of the distance travelled by the radio echo is also described.
It also shows the overlap of the measurements carried out on the same event by different observers by recording the temporal sequence and hypothesizes a method for calculating the meteor speed starting from the delay times recorded by each individual observation.

1 What is CARMELO?

The CARMELO project for radio meteor reception is described on the main page of the CARMELO website[8]. Another description appeared in this Journal (Barbieri and Brando, 2022), while the description of its first months of operation were published in the same Journal (Barbieri et al., 2023).

To briefly summarize here what is described in the aforementioned articles, CARMELO (Cheap Amateur Radio Meteor Echoes LOgger) essentially consists of two units: the receiving device and the server that processes the data received.

The device:
The apparatus consists of a receiver which cost is affordable for the majority of interested amateur astronomers or radio amateurs and it is entirely digital. Unlike all other amateur meteor scatter experiences, with the CARMELO radio receivers no personal computers are needed.

Consequently, the observations made from multiple observers are of the same type and recorded with the same standard. A microprocessor (Raspberry) essentially performs three functions:

- Operates an SDR (Software Defined Radio) dongle that tunes to the user’s chosen transmitter frequency.
- Samples the radio signal, calculates its FFT, measuring amplitude and frequency and recognizes the presence of a meteor echo. As a result, the interference and satellite signals are not detected.
- Writes data to a log file which is transferred to the server.

The device must be connected to an antenna suitable for receiving the chosen frequency, correctly oriented and positioned in an open place and as far as possible from the ground or buildings. It must also be connected to a modem that allows access to the internet.

The server:
The server receives data in real time. Since the data is generated by identical equipment and identical software, all is based on a single standard and therefore compatible with each other.

The server generates some pages which are available to the user. In these pages you can find:

- The distribution of CARMELO receivers across the territory.
- The statistic of the number of events recorded hour by hour in which it is possible to recognize the trend of the meteor shower activity.
- Each recorded event of the current week is graphically represented in order to identify for each: signal the amplitude, echo duration and the observer.
- By choosing a single meteor in this graphic representation, the user can open a new page which graphically represents the two measured data with the FFT: namely the waveform and the received frequency.
- If the chosen meteor has been observed by more than three observers simultaneously, the user can superimpose the various waveforms, allowing the analysis of the different reception times simply by clicking the appropriate button.

2 The CARMELO receiver network

The main difference between professional and amateur meteor radar lies in whether or not they have a dedicated transmitter. Amateurs use other people’s transmitters: with great power, with a frequency in the VHF (Very High Frequency) range and positioned at a large distance. Unfortunately, the analogue standard television broadcasting switch off in favor of the digital one and the

[8] http://www.astrofiliabologna.it/carmelo

transmigration of emissions to UHF has deprived amateur observers of many usable transmitters.

This conversion occurred first in Europe and then in the USA. In fact, now in the European territory the best, if not only usable transmitter, is the Graves military transmitter, while in the USA the few digital terrestrial broadcasts that remained on the VHF have drastically reduced their power. For this reason, the CARMEL0 installed in the USA now has much lower numbers of reception compared to previous years. At the time of writing, the functioning CARMELO network has one receiver in the USA, a dozen receivers in Italy and one in Croatia.

3 The events page

The events page records all the meteors observed by the network in the last week. Each event is plotted with the recording time on the abscissa scale and with the maximum radioelectric power on the ordinate axis.

Each event is also characterized by a symbol and a color corresponding to the observer who recorded that event. The size of the sign is proportional to the duration of the recording. By positioning the mouse over each event, a box appears which summarizes the essential data of that recording; all of this is automatic.

4 The waveforms

By clicking on the event, it is possible to see the waveform and the frequency simultaneously. This is possible because the server plots the result obtained from the FFT calculation carried out on each single sampling carried out on the radio meteor echo.

The waveforms are of various types: from those more similar to pulses which are characteristic for underdense meteors to the longer and flatter one's characteristic of overdense meteors.

The durations vary from about fifty milliseconds to several seconds. The lower limit of the duration of the detection of underdense meteors is given by the length of the sampling: in CARMELO, to identify a meteor, at least two consecutive samplings are needed.

The duration of each single sampling depends on the performance of the microprocessors: and ranges from a minimum of 8 to a maximum of 20 milliseconds. We have noticed that apparently identical Raspberry Pi4s, paired with identical dongles while running the same program, do not have the same speed. Using the new Raspberry Pi5 the speed increases by approximately 25%.

Undersense meteors show the descending curve which is expected considering the diffusion of the ionized plasma cylinder through free ion-electron recombination.

Another possible interpretation concerns the functioning of the transmitter, which, as mentioned, is a military radar. We do not have precise information about it and therefore we cannot know if the transmitted power undergoes variations over time such as to justify this type of variations in the received signal, also because these variations, as mentioned, do not have a pattern that is regularly repeated.

The waveforms illustrated so far concern the echoes reception coming from the reflection point *P* along the plasma cylinder formed by the ionization and therefore by the creation of free electrons, see *Figure 3*.

At point *P* the fundamental conditions of reflection occur:

- At this point the incidence angle is equal to the reflection angle.
- *P* is also the tangent point between the straight line representing the meteor and the ellipse which has the transmitter and receiver as foci.
- Furthermore, the plane on which the *TPR* triangle lies is orthogonal to the meteor trajectory. (Cis Verbeeck, Jean-Louis Rault, 2022)

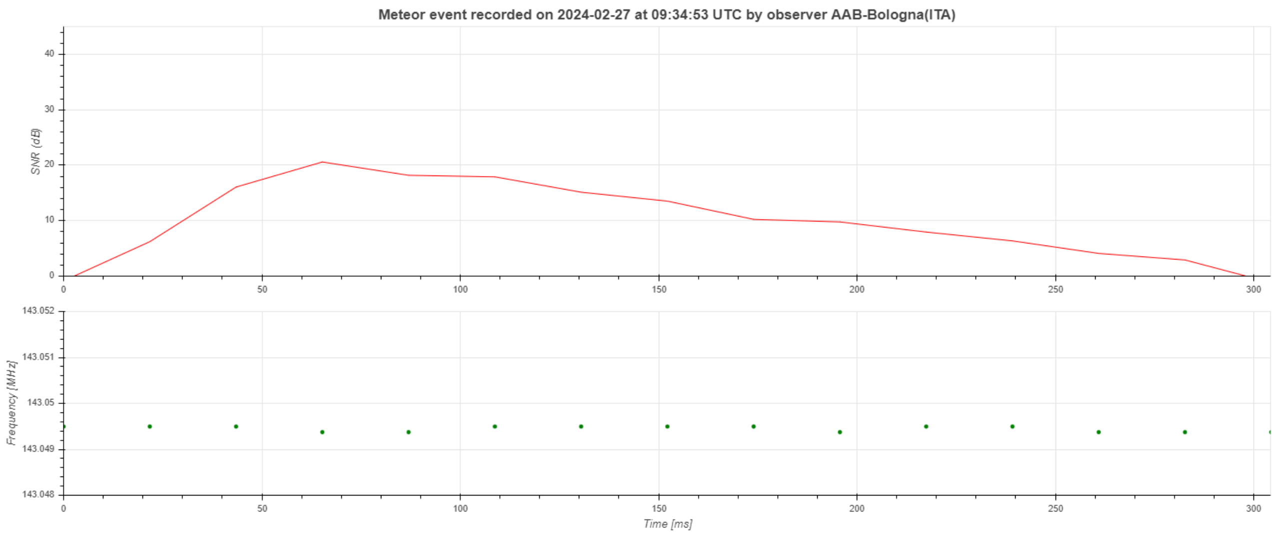

Figure 1 – Graph with waveform (above in red) and frequency (below in green).

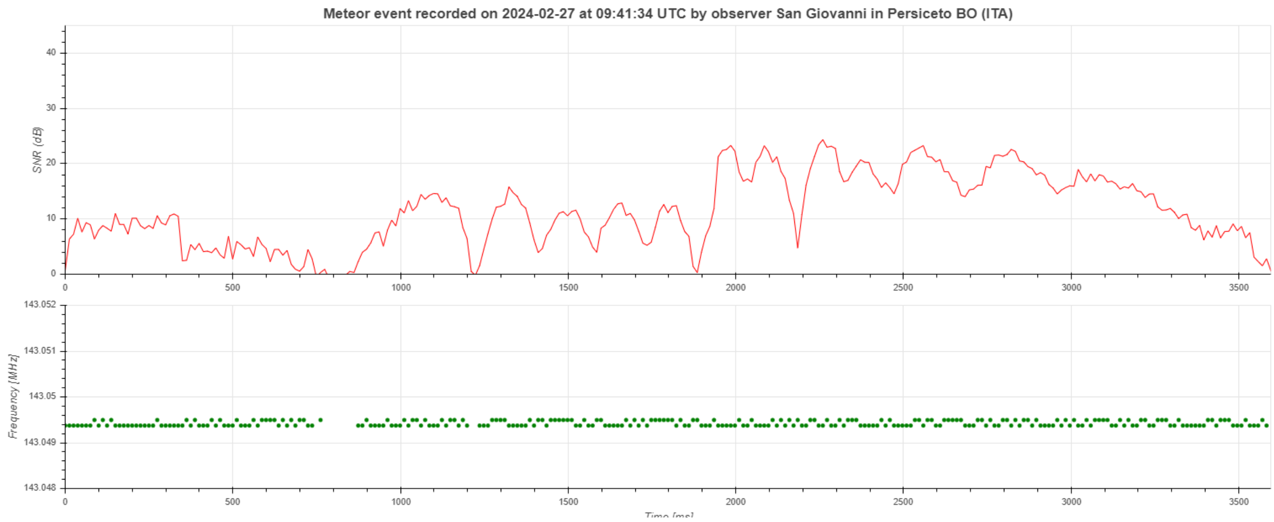

Figure 2 – Oscillations.

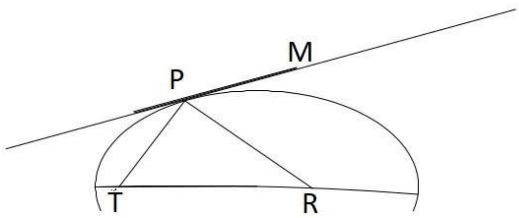

Figure 3 – The reflection condition: *T* is the transmitter, *R* the receiver, *P* the reflection point placed on the cylinder of ionized electrons.

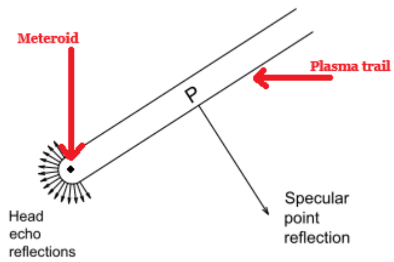

Figure 4 – Artistic representation of the two types of reflection.

5 The head echo

As mentioned, without the realization of the specular reflection condition, reception does not occur; it is possible, however, that before the creation of this cylinder, or even regardless of it, it is possible for a receiver to pick up the head echo.

The head echo is generated in the front part of the meteor radio where the meteoroid ablation generates the plasma first appearance which takes on a spheroidal shape.

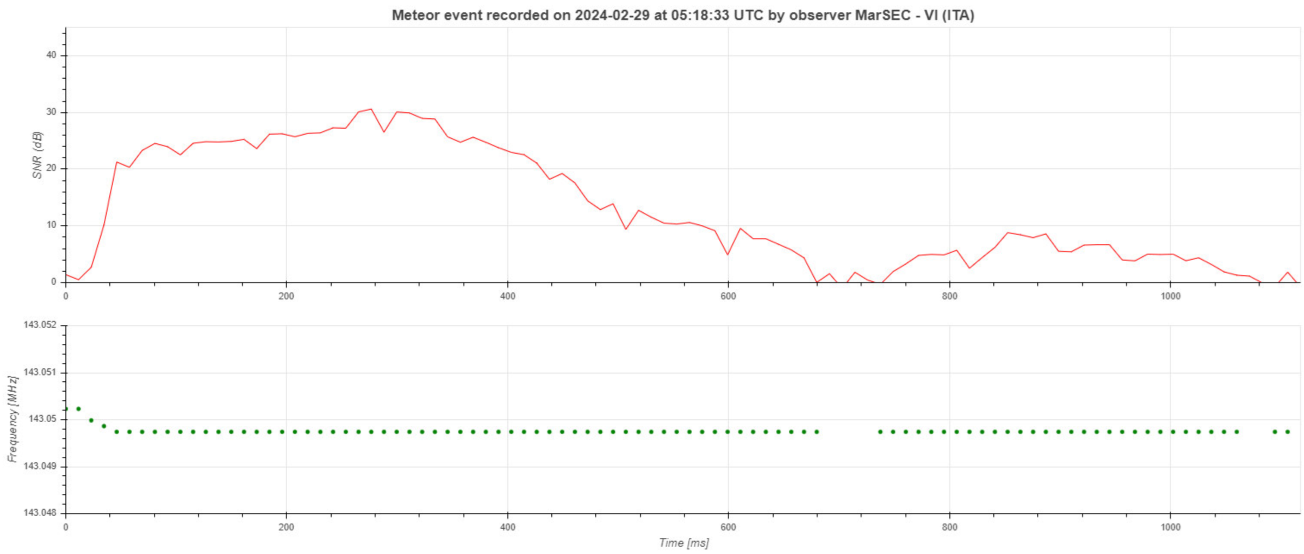

Figure 5 – The head echo. In the first 50 milliseconds the signal comes from the plasma sphere caused by the advancement of the meteor in the ionosphere. The received power (in red) is low and the frequency (in green) shows the Doppler shift. Around 50 milliseconds the meteoroid reached the reflection point *P*, orthogonal to the observer's point of view. The Doppler shift fades out and the reflection of the ionized cylinder overrides that of the receding head echo.

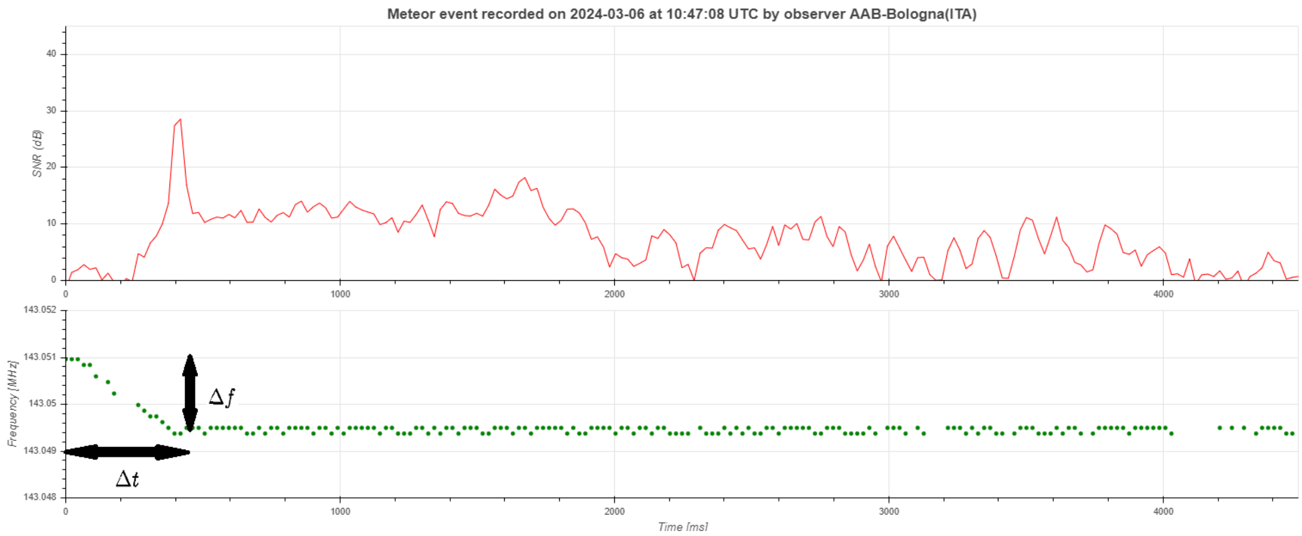

Figure 6 – Δ*f* and Δ*t* in the Doppler shift.

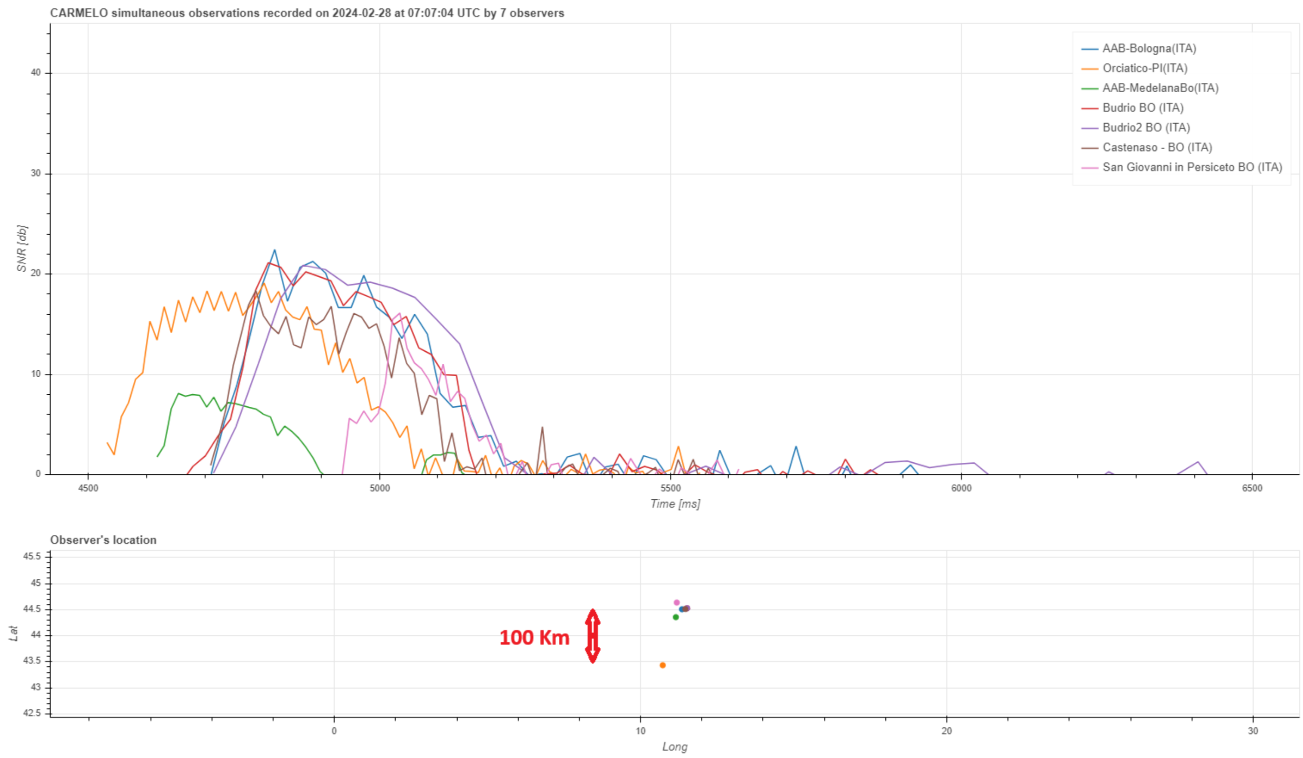

Figure 7 – Overlay of waveforms coming from 7 different receivers. In the upper part of the graph, you can see the different amplitudes of the radioelectric power received and the different reception times. In the lower part the location of the interested observatories on the territory is reproduced.

On this shape the reflection is omnidirectional and the reception is therefore admissible regardless of the reflection conditions typical of the specular reflection, described above.

In the case of the meteor in *Figure 5* we note that the first 50 milliseconds describe the head echo: the signal is very weak compared to that due to the cylinder of free electrons that is created after the first 50 milliseconds. Despite the small amount of power received, the Doppler shift due to the meteor speed is evident.

CARMELO records the frequency of each sampling with a precision of ± 61 Hz. The ratio between Δ*f* and Δ*t* gives us the Doppler shift slope. This slope depends on the meteor frequency and on the geometry determined by the mutual position of the meteor trail, the transmitter and the receiver.

6 Simultaneous receptions

The network of receivers in operation at the time of writing covers a small part of our country (Italy). The distances between the observatories vary between tens of kilometers and up to a few hundred kilometers.

Many meteor echoes are simultaneously observed by multiple observers: in this case the user can view all the superimposed waveforms by clicking on the "see simultaneous receptions" button. As you can see, simultaneous receptions of the same event are more likely with nearby receivers, but above all for higher power echoes, it happens that they can also be seen from relatively distant locations.

The waveforms have different amplitudes: this depends on various factors: first of all the antennas do not all have the same gain, and above all, not all observation conditions are optimal: some observatories have buildings or land close to the antenna, thus moving away from the conditions of best reception, but the essential fact that different observers receive the signal from different points of the trajectory must be taken into consideration, and it is therefore possible that the free electrons density in different trajectory points is, in fact, different. A point with lower ionization therefore involves less reflection and a faster process of recombination of ions and free electrons with consequent shorter duration of the echo.

The differences between the waveforms recorded by observers distant from each other cannot always be explained with the arguments presented above; there are cases in which different waveforms can be interpreted as different behaviors of the radio meteor at different points of its trajectory. The graph in *Figure 8* shows one of the cases we sometimes encounter.

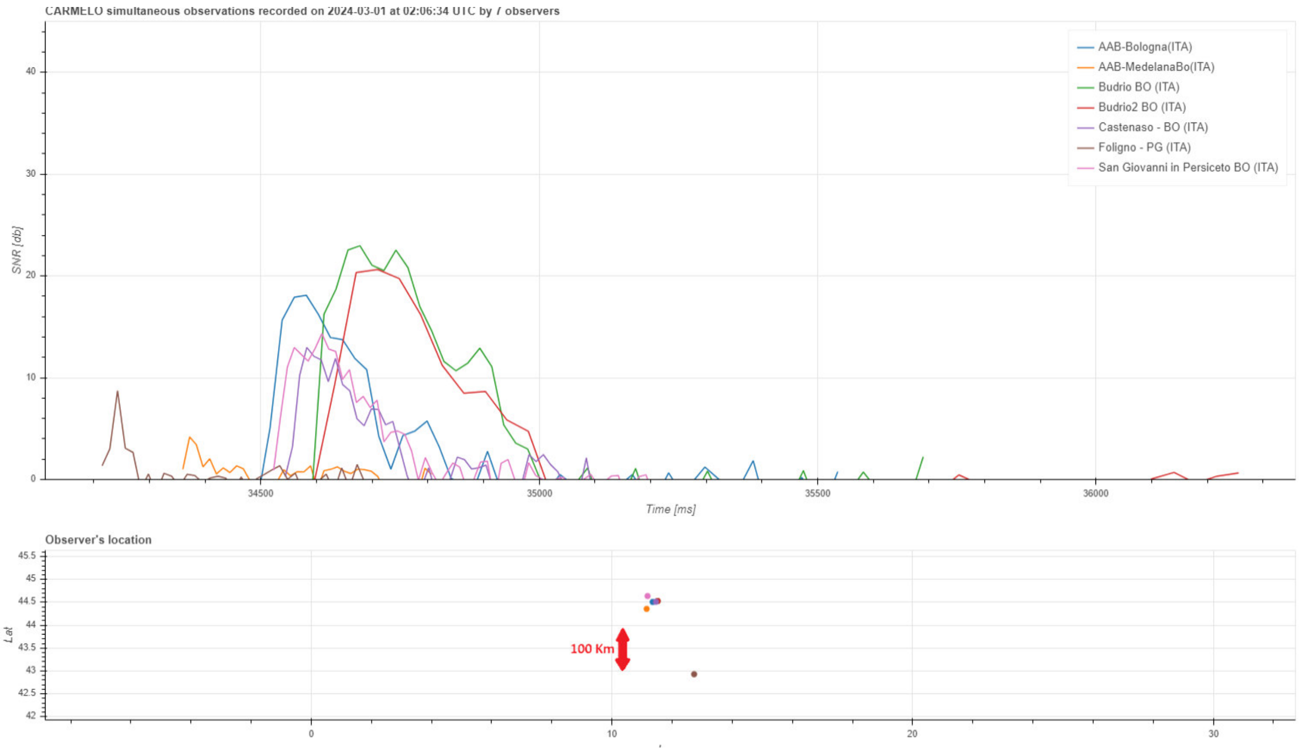

Figure 8 – After about a second and several tens of km travelled, the radio meteor shows a sudden increase in reflection.

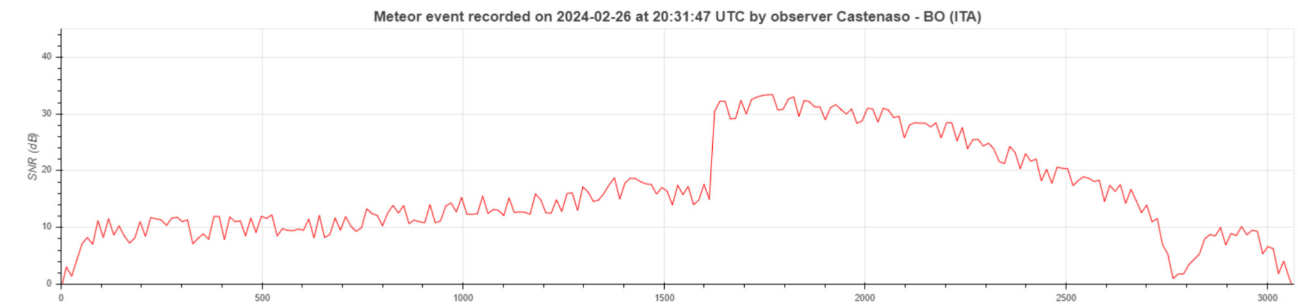

Figure 9 – Another case of sudden increase in power received.

The last observer recorded a sudden increase in received power. The explanation for this fact may have been traced back to a measurement error of the equipment, but this explanation is not supported by the experience we have acquired in three continuous years of CARMELO operation.

It could otherwise be hypothesized that the cause of this increase in power lies in the functioning of the transmitter, and in particular in the variation in power due to the rotation of the radiation beam of its antennas. Indeed, the Graves transmitter, being a military transmitter, has technical parameters that are not easily known and the little information in our possession is scarce and dated.

The impression we have after many years of observation is that something has changed in the time and that the discontinuities in the sky sweep carried out by Graves' antennas have, if not disappeared, drastically decreased. Furthermore, the fact that the increase in reception of this radio meteor is around ten dB, and thus vertical, and above all detected by a single observer, would rule out this hypothesis.

As an alternative to the explanations set out above, one could hypothesize that at the instant of the increase in the received power CARMELO "saw" a fragmentation of the meteoroid and a consequent increase in the production of ionized plasma. Although uncommon, the observation of sudden increases in received power also occurs in other cases.

The most interesting observation concerns the temporal sequence of the rising edges present in the recorded waveforms by each observer.

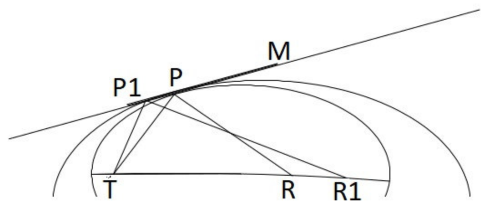

Figure 10 – Different receivers see the same meteor at different points on its trajectory.

If we hypothesize that the instant in which the reception presents its initial rising edge is the one in which the radio meteor appears at the specular reception points P_1, P_2,… .P_n we can associate the different times t_1,t_2,….t_n to these transits.

By comparing the various times of increasing waveforms it is possible to see the progression in space of the different moments in which the cylinder of free electrons appears for each observer.

In simultaneous receptions the delay times follow a sequence which has a clear counterpart in the location on the territory: for example, in *Figure 11* we can see how the temporal progression suggests a trajectory from south west to north east. In some cases, there are simultaneous receptions even between very distant receivers.

7 Velocity calculation

The images displayed here are a small sample of the amount of data that the CARMELO network provides and makes available to observers and enthusiasts, continuously and in real time for each observed meteor.

Are the data provided by the observations of the CARMELO network sufficient to calculate the speed of the meteors? This objective has so far been a forbidden dream for all amateur astronomers, that is, for all those who observe radio meteors using continuous wave transmitters.

The absence of a pulsed signal in fact prevents any sort of triangulation and measurement on the different times of the progressing meteor trajectory of the individual echoes received by multiple receivers. We can consider two different approaches: that of the head echoes Doppler shifts and that of the simultaneous observed time delays.

Figure 11 – Simultaneous reception from three observers: the waveforms are similar.

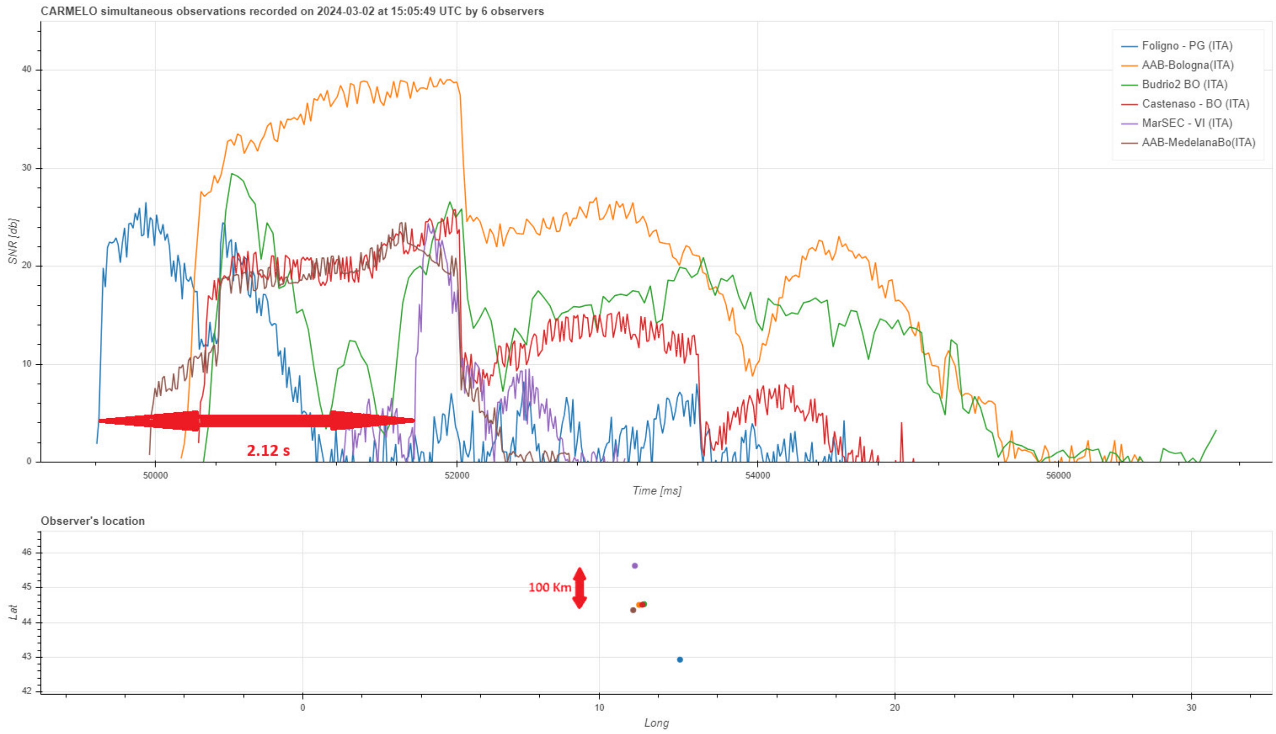

Figure 12 – Simultaneous reception performed by 6 observers. The two most distant are over 300 km away. The delay between the two rising edges is 2.12 seconds.

In the first case the absence of information about the meteor trail position in the forward scatter configuration prevent us from writing an algorithm suitable for solving the problem. As already said in *Section 5* head echoes are not always present in receptions and this is due to at least two factors: first of all, the fact that they are very weak and therefore almost always indistinguishable from noise, secondly because due to the geometric orientation of the track the head echo may not always appear before the meteor transit point *P* of the specular reflection.

The CARMELO network data provide us with the delay times of the wave fronts appearance at the specular reception points $P_1, P_2,\ldots,P_n$ observed along the meteor's path. The question arises whether it is possible to write a set of equations that is able to place the aforementioned points along the tangent line to the *n* ellipsoids having as foci *T* and the points $R_1, R_2,\ldots,R_n$ represented in *Figure 10*. In this way it would be possible to outline both the trajectory and the speed.

To this end it is possible to search for the points $P_1, P_2,\ldots,P_n$ and their coordinates using the method described by M. T. German (2023) by calculating the shortest distance in the path $T\ P_n\ \ R_n$ between the infinite points of the meteor's trajectory. Here too, comparison with the video recordings of the aforementioned networks will be necessary.

8 Conclusions

The observation of the hourly rate of meteoric activity has so far been the only result of the experiences of receiving radio meteors with the meteorscatter method in the amateur field. The CARMELO project allows us to go beyond this objective.

With CARMELO it is possible to see in real time the waveform of each observed radio meteor and qualitatively analyze the physics of each event: from the head echo to the creation of the reflecting plasma cylinder up to its dissolution.

On a quantitative level, the data produced allow us to investigate the Doppler shift created in the head echo and to evaluate the speed of the meteor as a function of the meteor-receiver distance.

The simultaneous reception of the same event by multiple observers located across the territory allows us to obtain the different times in which the radio meteor reaches the specular reflection point for each of the observers. The development of a geometric analysis of the temporal sequence can lead to the velocity measurement and the evaluation of the trajectory.

The next step will be to choose one or more events that have a simultaneous visual observation recorded in one of the various networks based on dedicated video cameras, and from these data compare position, speed and trajectory in search of resemblances both in the field of head echo Doppler shift measurement, and in the temporal sequence of simultaneous receptions.

Acknowledgment

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