RETRAM: A network of passive radars to detect and track meteors

First results

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Abstract— ***when a high speed meteoroid enters atmosphere, its ablation produced by friction with the air molecules ionizes the surrounding gas into a plasma reflecting electromagnetic waves. This phenomenon is well known for radars where the plasma creates a moving target reflecting back the transmitted pulses. This reflection mechanism is also the key for point to point communications where specific wireless systems are designed to use these opportunistic reflectors to open obstructed channels. Most meteoroids fully ablate during their atmospheric entry, from which micrometeorites will eventually reach the ground. For more massive objects which can survive to their atmospheric entry, it is of high interest for scientists and astronomers to collect fallen meteorites.***

Meteor detection and tracking is the core research work done in the RETRAM group. Conversely to most of the published work on the topic, this project uses passive radar techniques and continuous processing to detect falling objects and to try to estimate their trajectory. Experiment started in the vicinity of Paris, France.

This paper describes the underlying physics and architecture of the system, the different illuminators of opportunity used and gives some results for the main showers since 2012.

Keywords— ***meteor scatter, meteor detection, passive radar, VOR FM passive radar***

I. INTRODUCTION

Earth continuously crosses the orbit of meteoroids of different sizes, which can thus penetrate its atmosphere at velocities ranging from 11 to 72 km per second. While entering its upper layers, the meteoroid starts ablating, ionizing the air molecules on its path. At the beginning of the entry, the meteor itself can be detected using classical radar techniques, as long as the power involved and used wavelength are compatible with the target shape and velocity.

The ionized remaining train acts as an electromagnetic reflector with a maximum reflectivity in the VHF band mainly, and less in the UHF range [4]. This train is then extending downwards at the speed of the meteor head, and is moving according to the winds blowing in the atmosphere (in this paper we will name 'meteor trail' the region of the atmosphere becoming ionized by the meteor). This trail will also be detected by radars, as long as the plasma will be reflective enough at the transmitted signal wavelength.

Different meteor detection experiments have been conducted using active radars, like the ARPA Long-Range Tracking and Instrumentation Radar (ALTAIR) [1][2] or EISCAT [3]. These trials have shown head echo and trail can be detected efficiently, and provided a lot of useful data to understand the phenomenon.

Well suited for limited-duration experiments, active radar is maybe not the best option for a continuous survey of a wide area at limited cost. For this reason, a passive-radar technique could be an interesting alternative and this was experimented by RETRAM.

This paper is organized as follows: after detailing the considered phenomenology, a quick summary of the selected illuminators of opportunity is given followed by the description of the system setup. Then, signal processing performed for meteor detection is explained and finally preliminary results are discussed and the expected architecture for a networked version of the project is finally proposed.

II. PHENOMENOLOGY

A simple model of the meteor radio reflection is shown in **figure 1**. The transmitter ***Tx*** broadcasts RF signal in all directions, a part of this signal reaches the receiver ***Rx*** (path 1). Note that in real cases, signals coming from other transmitters are also reaching the receiver and will create interferences, but for simplification of the illustration, these undesired signals are not shown here. Thanks to the signal processing, they will be greatly attenuated by the correlation with the reference signal (matched filtering).

When a meteor *M* falls through the increasing density atmosphere layers, the meteor head acts as any body immersed in a RF field and scatters back incoming signals (path 2). The meteor ionized train, containing particles from the meteor body and heated atmosphere acting as plasma, reflects also a portion of the incoming signals (path 3).

In the following, we consider:

1. the Direct path : energy from transmitter to receiver,
2. the Meteor head reflection : energy reflected by the falling body reaching the receiver,

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3. The Meteor trail reflection: energy reflected to ground by the ionized path of the meteor, because of plasma effect of meteor particles resulting from main body ablation.

Energy P_r reaching receiver from paths (2) and (3) is directly related to the classical bistatic radar equation:

$$P_R = \frac{P_T.g_t.g_r.\sigma.\lambda^2}{(4\pi)^3.L.d_{tx}^2.d_{rx}^2} \quad (1)$$

Where $\boldsymbol{P_t}$ is the power at the transmitter, $\boldsymbol{g_t}$ and $\boldsymbol{g_r}$ respectively antenna gains at transmitter and receiver, $\boldsymbol{\sigma}$ the bistatic radar cross section, $\boldsymbol{d_{tx}}$ distance from object to transmitter, $\boldsymbol{d_{rx}}$ distance from object to receiver, and $\boldsymbol{L}$ the total losses.

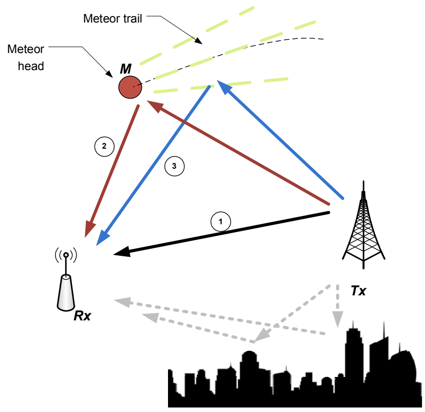

Figure 1 – Model of scattering

Assuming the transmitted signal is written as $tx(t) = A(t).e^{j\omega(t).t+\Theta(t)}$, motion of the meteor head and trail generate Doppler shift of the reflected signal according to equation 2:

$$s(t) = A(t).e^{j\omega(t).t+\Theta(t)}.e^{jD_{opp}(t).t} \quad (2)$$

where $D_{opp}(t) = \frac{-1}{\lambda}\left[\frac{\partial d_{rx}}{\partial t} + \frac{\partial d_{tx}}{\partial t}\right]$

Beside these reflections, ground, hills and man-made buildings act as secondary reflectors for the transmitted signal, hence bringing to receiver other delayed copies of the broadcasted reference signal. The total received signal can be written as proposed in equation 3:

$$rx(t) = k.tx(t-\tau_1) + \sum_n \alpha_n.tx(t-\tau_n).e^{jD_{opp}(t)} + \sum_m \beta_n.tx(t-\tau_m) + \eta$$

(3)

Where $\boldsymbol{k}$ models the line of sight attenuation, τ_1 is the direct-path delay, τ_n delay caused by the $\boldsymbol{n}$ multiple reflections on the trail and head, τ_m delay caused by the $\boldsymbol{m}$ multiple reflections on the environment, and η the noise.

The signal processing will try to recover the delays τ_n and bistatic Doppler to estimate meteor position.

III. ILLUMINATOR SELECTION

According to [4] VHF or UHF illuminators would produce roughly same detection performances, but the lack of transmitters directed towards the sky in the highest frequencies limited the experiments in the VHF range. In the search for ground transmitters with sufficient density to have a national coverage with always more than one signal reaching the receiver, the following illuminators were tried:

1. Navigation Aid Transmitters ("*NavAids*") and more precisely the VOR (VHF Omni Range) used for aircraft route navigation and installed years ago. More than one hundred VOR transmitters are in service across France,
2. FM broadcast transmitters,
3. Strong narrow-band beacons (50 and 143 MHz).

The two first illuminators are transmitting in the 80 to 120 MHz band, but are significantly different:

1. FM broadcast stations use high power amplifiers (several kilowatts) but with radiation patterns optimized for ground illumination. Transmitted signal occupies up to 120 KHz (stereo audio + RDS + SCA), with auto-correlation properties depending on modulation content.
2. VOR transmitters are low power (from 100 to 200 Watts) and radiating to sky for aircrafts, but transmitted signal is very narrow bandwidth, giving poor range resolution. See [5] for more details on VOR transmitters.

Trials were conducted in early 2012, but finally VOR transmitters were abandoned for FM, as the transmitted signal by VORs suffers limited range ambiguity properties. Narrow band beacons have also been tried but require 'Doppler only' processing to estimate position, and were finally discarded.

These tests, in particular trials where 4 VOR stations around Paris were recorded, showed a meteor reflectivity suitable for VHF measurements. Simultaneous Doppler shifts on all transmitters proved the phenomenon was in the region and suggested it could be measured using FM signals.

IV. SYSTEM SETUP

The experimental setup is made of two yagi antennas for the FM broadcast. To detect local events, the antennas are directed towards the sky and oriented so that, by combining the signals collected, they have an omnidirectional pattern in the horizontal plane. The simulation plots in figure 2 were done with NEC Method of Moments code [6] and show the expected radiation patterns for the FM yagi pair. Resulting gain drops by around 6 dB for elevation angles around 20 degrees and about 20 dB for lower angles, but does not show notches and good signal collection for most of the targets above the antennas can be expected. This low-angle attenuation is very helpful in the direct-path rejection (see V).

The two antennas are placed on top of a metallic shelter, 2.5 meters above the ground, and the distance between the two yagis is around a half wavelength. These antennas are connected to a custom band-pass filtering and amplifying module to prepare the signal for direct sampling by a 4 channels ICS-554 acquisition board [7].

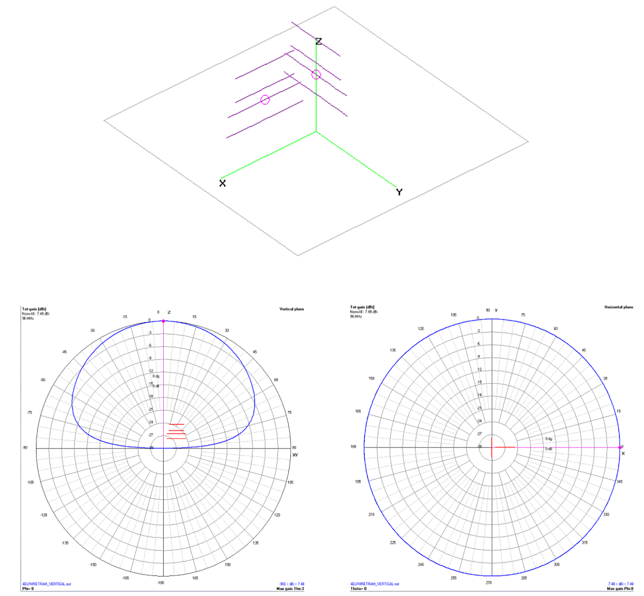

Figure 2 - Antenna wire frame (top) and radiation pattern (bottom) simulations

For each channel, band-pass filters and amplifiers have been designed to have a global gain of around 45 dB, with a bandwidth of 2 MHz. This acquisition board is driven by an external RF synthesizer generating an 80 MHz sampling clock, locked by a GPS disciplined oscillator.

The complete architecture is described in figure 3.

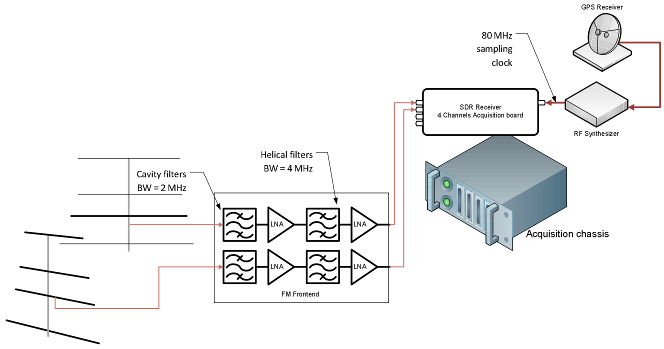

Figure 3 – System setup

V. DETECTING AND ESTIMATING METEOR POSITION- SIGNAL PROCESSING

A classical passive-radar processing is applied to the collected signals. This processing flow is described in figure 4. At the end of the process, we expect a list of detections, formed by a set of {bistatic distance, bistatic Doppler} pairs.

Doppler shift $D_{opp}(t)$ and path delay τ_n are estimated using cross-correlation: This processing requires a measurement channel (*target path* in figure), containing possible targets, and frequency shifted replicas of a reference signal (*direct path* in figure).

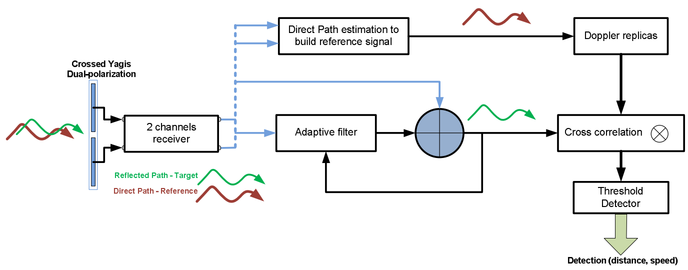

Figure 4 –Signal processing

As shown by equation 3, these two terms are present but added to direct path and clutter echoes. Processing collected signals without attenuation of these undesired quantities would not enable proper detection of weak targets and adaptative filtering has been selected for its good rejection properties. This technique is described in depth in [8] and assumes the clutter echoes are mainly scattered from the k first range bins and searches for an optimal estimation of the clutter plus direct path subspace. Then, a projection orthogonal to this space is applied to the incoming signal for maximal rejection.

Different trials were performed to estimate the depth of range bins potentially backscattering broadcasted signals. To illustrate the efficiency of the rejection, figure 5 shows the efficiency of the rejection technique used.

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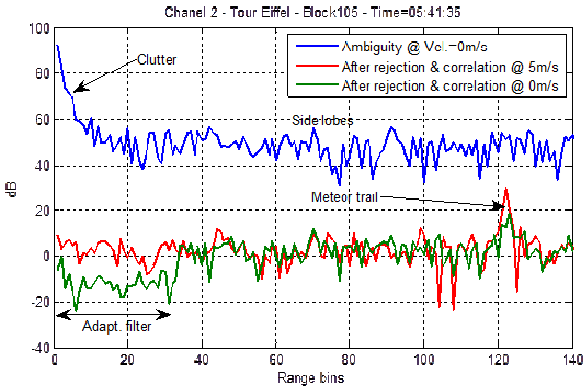

Figure 5 - Clutter rejection efficiency

This plot is extracted from a meteor detection campaign where the used sampling rate was 125 KHz (acquisition card post digital down-converter filters were set at 80% bandwidth, hence leading to a resulting band of 100 KHz). This plot shows:

1. In blue, the output of the cross-correlation cut at 0 Hz, without rejection. Direct path and side lobe are decreasing after range bin 20 but are still very high, showing no clear target coming out.
2. An adaptive filter with 32 coefficients is used and attenuates the clutter, as shown by the red and green plots.

A range cut at 0 Hz (green plot) shows the attenuation over the 32 first bins, while the red (range cut at 5 m/s) shows a meteor trail detected in range cell 122. We clearly see on the figure that without direct path attenuation, it would have not been possible to detect the meteor trail, around 20dB below clutter level.

Next step consists in identifying the most probable targets by searching for local maxima in this Range-Doppler map.

This detection is made using a Cell Averaging (CA)-CFAR algorithm. We tuned this algorithm so that it takes into account:

- the high Doppler width of meteor signals,
- the varying and typically low resolution of FM signals (~ 100 kHz BW).

The cells to evaluate the level of the noise floor (around the cell under test) are chosen mostly along the Doppler axis, and range-shifted from the cell under test (adaptive, depending on the current BW). Thresholds were calculated using the radar characteristics and adjusted experimentally.

Finally, an extraction module aggregates previously detected cells to form plots and estimate their range/Doppler characteristics. Moreover, it suppresses detections due to waveform side lobes.

Bistatic distance sets the possible position for the detected meteor to be an ellipsoid whose foci are the transmitter and the receiver, as illustrated by figure 6.

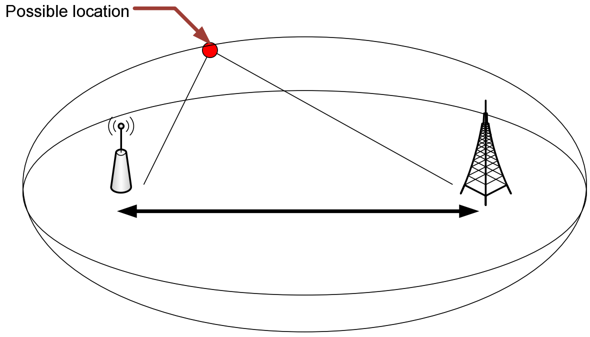

Figure 6 – Bistatic ellipsoid

To have the actual position of the meteor, more than one transmitter must be used to remove ambiguity. Intersections of these ellipses give the possible target position as shows figure 7.

Practically, the challenge is to find enough FM transmitters non-collocated for spatial diversity. For usual low altitude targets like planes, it is generally difficult to estimate actual height because of typical range-cell size obtained with FM signals (more than 3 km).

In meteor case, the high altitude of the falling object suggests a better accuracy can be expected, and this is still under evaluation at time of writing.

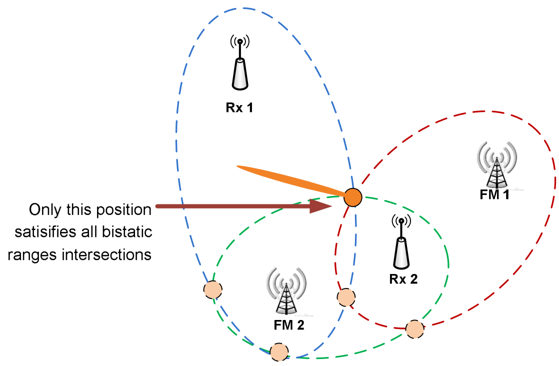

Figure 7 – Multistatic setup for meteor localization

VI. First Results

For the trials, signal acquisitions were performed during the main meteor showers and data post processed for code validation. During the Perseids for example (August 2013), a continuous acquisition over 4 days was performed, using the Eiffel Tower and Chartres FM transmitters. The receiver was placed in Orsay, giving baselines respectively around 20 and 80 km.

Figure 8 gives example detection (dotted circle at bottom of figure) where red circles 1 and 2 in figure are airliners (top of the figure, low bistatic distances).

This target is the meteor trail because of the limited bistatic Doppler on both illuminators, and this conclusion was confirmed by optical observation (video record made by amateur astronomer).

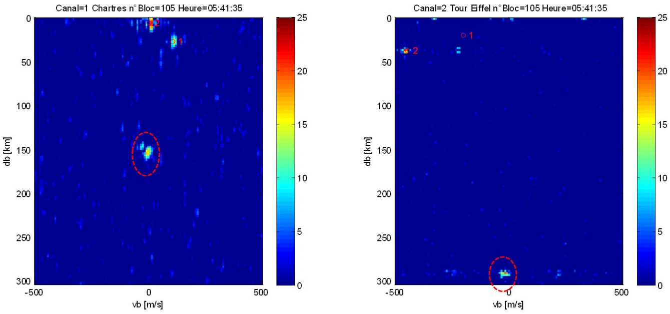

Figure 8 - Example detection for the Perseids 2013

The evolution over time of the bistatic distance is shown in figure 9, for both baselines. On these plots, the frame duration is around 300 milliseconds and colour is a function of the RCS in arbitrary units.

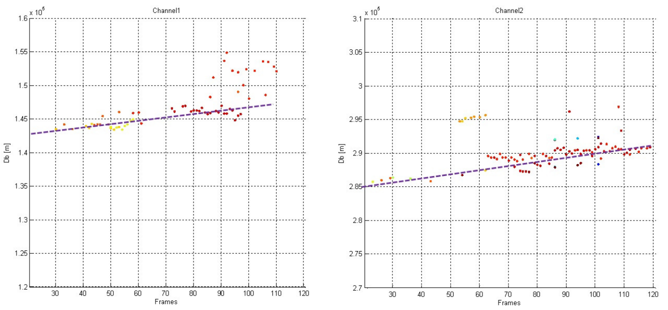

Figure 9 - Trail bistatic distance over time - Perseids 2013

It can be noticed that selected FM transmitters had still enough energy at altitudes of around 10 km (usual trail 'end of life' altitude) and bistatic distances of around 280 kilometers, this is much more than the usually expected coverage.

VII. Network Extension

As discussed previously and depicted in figure 7, the best solution for an accurate estimation of the meteor position is to extend the number of receivers and transmitters involved in the signal processing. Two main strategies can be used for such a networked radar system:

1. Merge raw RF data to a centralized signal processing system,
2. Detect locally possible targets and merge their estimated position for consolidation.

First approach requires time synchronization between receivers, to get time-stamped signals for cross-correlation. This suggests adding expensive GPS-disciplined oscillators for each station.

Second approach is less greedy in terms of network bandwidth, but requires more powerful local computers to perform the adaptive filtering and target extraction in real-time. Here the time synchronization constraint is relaxed as the cross-correlation is done locally.

To evaluate possible implementations, two new RETRAM stations are under deployment around Paris for benchmarking.

The expected system is described in figure 10 where the second mode (local detection and target position fusion) is shown.

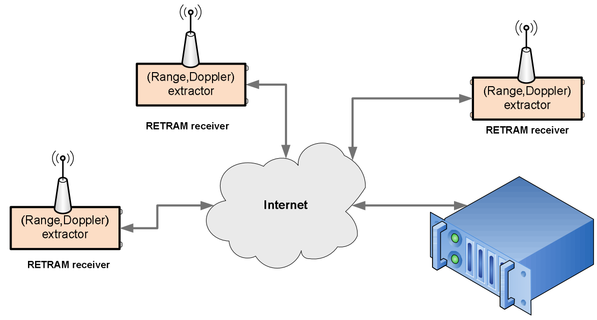

Figure 10 - Network of stations

This small network of passive radars will be used as a mockup for a possibly wider system, to cover a much bigger area.

VIII. Conclusion

Data recorded during the main showers over 2012 and 2013 have shown the feasibility and efficiency of using passive radar detection and tracking techniques to meteors. Initially started with VOR transmitters for good coverage, the experiment continued with FM broadcast signals, giving unexpected high altitude detection capabilities. New recording stations will be installed and interconnected to experiment real time continuous detection and position estimation.

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