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Propagation and plasmas: New challenges, new applications

Earth–ionosphere couplings, magnetic storms, seismic precursors and TLEs: Results and prospects of the [SQUID]^2 system in the low-noise underground laboratory of Rustrel-Pays d'Apt

Couplages Terre–ionosphère, orages magnétiques, précurseurs sismiques et sylphes : résultats et prospects du système [SQUID]^2 au laboratoire souterrain de Rustrel-Pays d'Apt

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ABSTRACT

High sensitivity combined with an ultra-low-noise environment [SQUID]^2 magnetometer (Superconducting QUantum Interference Device with Shielding QUalified for Ionosphere Detection) allows the observation of Earth–ionosphere couplings. Namely:

- identification of a mesopause resonance mode excitable by P waves or by electric field as during the hour before the Sichuan earthquake (May 2008);
- S and T breathing modes of the Earth during quiet magnetic and seismic periods;
- worldwide signal integral of magnetic storms including polar contributions;
- signals in time correlation with sprites (Transient Luminous Events).

These results point to a worldwide network of at least a few stations of a similar type.

RÉSUMÉ

Grâce à sa sensibilité et son environnement très bas bruit, les couplages Terre–ionosphère sont observables par le magnétomètre [SQUID]^2 (Superconducting QUantum Interference Device with Shielding QUalified for Ionosphere Detection). Notamment :

- un mode de résonance de la mésopause excitable par les ondes P ou par champ électrique comme dans l'heure précédant le séisme de Sichuan en mai 2008 ;

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– les modes S et T de respiration du globe pendant des périodes de calme magnétique et sismique ;
– l'intégrale mondiale du signal des orages magnétiques y compris les contributions polaires ;
– des signaux associés aux sylphes.

Ceci permet d'envisager un réseau mondial de quelques stations de même type.

1. Introduction

[SQUID]^2 is a 3-axes low T_C SQUID magnetometer seated on the suspended floor located inside a capsule shielded against electromagnetic pulses produced by a nuclear blast (it is a former launching control room for missiles). Such a shielding permits the observation of the hydro-magnetic response to P waves from distant earthquakes arriving in the karstic system surrounding the capsule (Section 2). The emerging P wave into the atmosphere, reaches the mesopause 300 seconds later and excites a resonance mode in the tens of millihertz range, called the mesopause resonance. At such large wavelengths, wherever the event which takes place on Earth one is always in an electromagnetic near-field situation (Section 3). This resonant mode can also be excited by an electric field, as it has been observed by [SQUID]^2 for one hour before the Sichuan–Wenchuan quake in May 2008 (Section 4). For acoustic signals of much lower frequency than the mesopause resonance, the excitation of this resonance mode is not possible, but one can observe a global ionosphere movement at extremely low frequencies. Such is the case for the breathing modes of the Earth which are effectively observable by [SQUID]^2 during magnetically quiet days even in the absence of major earthquakes (Section 5).

The detection of a magnetic storm is nothing exceptional. Here, the capacity to take advantage of the full sensitivity of the SQUID magnetometer due to its enhanced shielding provides responses which are, to a first approximation, as rich as those recorded by conventional magnetic observatories at polar latitudes (Section 6). However, the signals are the worldwide magnetic responses. Not surprisingly [SQUID]^2 detects lightning sources of Transient Luminous Events (Section 7).

Perspectives and limitations of the interpretation of signals from a such instrument which is still unique point to the creation of a worldwide network even consisting of a minimal number of such stations (Section 8).

2. The instrument

2.1. Description

The seismic noise spectrum of LSBB area is near to the theoretical worldwide minima (Figs. 1 and 2).

This means that no movement of magnetic masses generated by mechanical parasitic movements can perturb magnetic observations. In addition to this seismic calm, the electromagnetic shielding results from the addition of natural shielding by

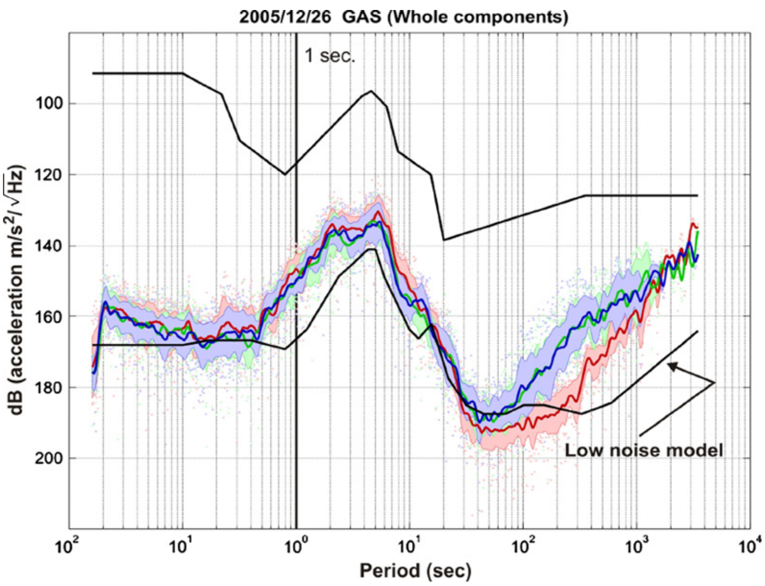

Fig. 1. Seismic noise spectrum recorded at LSBB. The black lower curve is the worldwide minimum model.

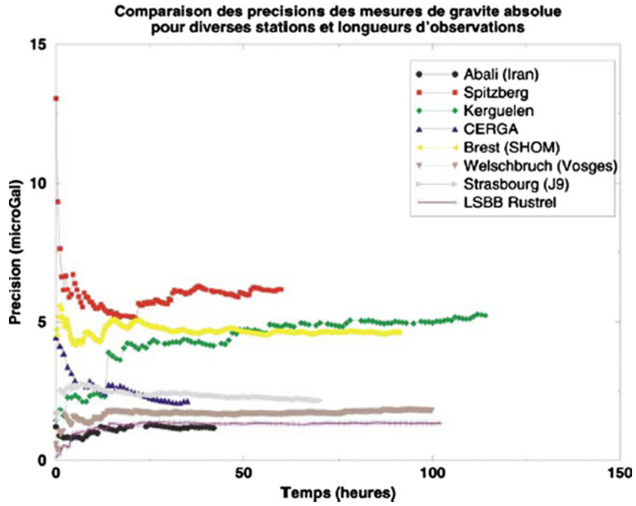

Fig. 2. Comparisons of gravity measured by the same gravimeter at different world locations. LSBB exhibits the smallest fluctuations with Abali in Persia (time in hours).

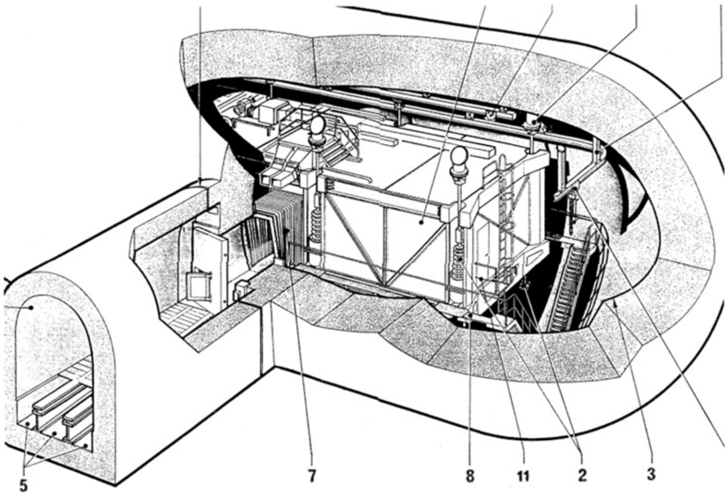

Fig. 3. Overview of the capsule and its 2 m thick reinforced concrete walls plus 2 cm of steel on the interior face. The suspended cabin in the center is kept in position by jacks and shock absorbers. This shielding is not amagnetic and contains no μ metal.

518 m of karst, plus two meters of reinforced concrete and finally by two centimeters of steel all over the capsule walls [1], where the magnetometer sits (Fig. 3). The absence of μ metal in this shielding makes it a prefect low frequency pass-band filter totally different from a zero gauss chamber. The capsule itself, a horizontal cylinder capped at both extremities by hemispheres, is roughly oriented North–South, it contains a suspended cabin (with a floor of 100 m^2) raised on jacks and shock absorbers.

2.2. Validation

The 3-axes low T_C SQUID sits on the floor of the cabin, decoupled from it by a sand box. The [SQUID]^2 noise baseline is 2 $fT/\sqrt{Hz}$ (Fig. 4), it is indeed the intrinsic noise of the SQUID alone in a zero gauss chamber. [SQUID]^2 is thus a low frequency pass-band filter [2].

The validation of the possibilities of this unusual combination of a SQUID magnetometer with such a shielding has appeared during the data collection which has aides in the characterization of this shielding. Simultaneously at the P wave arrival from an $M_w = 7.6$ earthquake (Bhuj, India) the SQUID has recorded a magnetic signal in the tens of picoteslas range: the magnetic-hydro-seismic response of the karstic system of the Plateau de Vaucluse into which the LSBB is embedded [3].

As a result a permanent 3-axes low T_C SQUID has been installed within the LSBB capsule. The magnetic recordings obtained by this system are in good agreement with a linear interpolation of those obtained by three surrounding magnetic

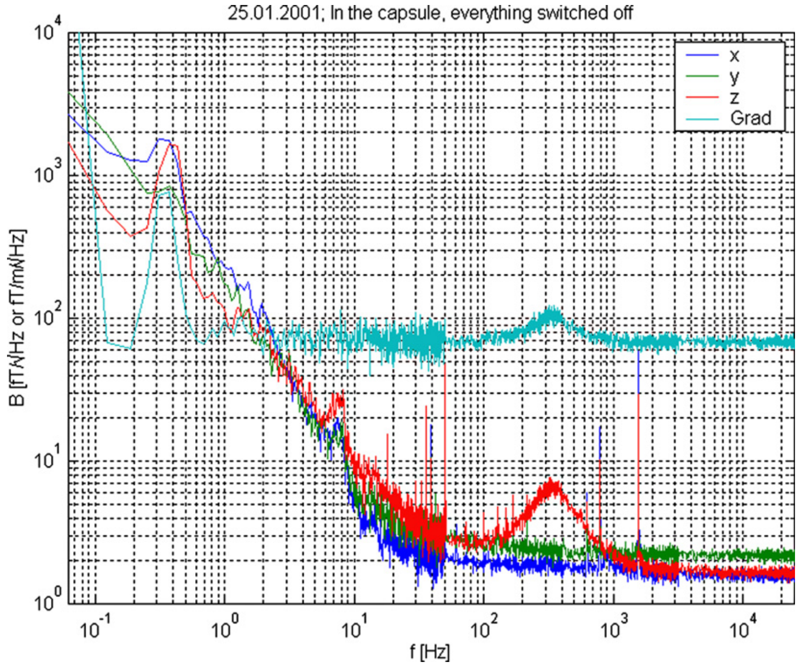

Fig. 4. 3-axes magnetic noise spectrum within the cabin (dark blue, red and green traces, the light blue one is a vertical gradient). The 350 Hz resonance is a SQUID holder resonance, towards 8 Hz one has the first Schumann resonance; around 0.6 Hz the oceanic swell [2].

observatories: Chambon la Forêt in France, Ebro in Spain, and Fürstenfeldbruck in Germany, their precision is limited to 0.1 nT [4].

3. Mesopause excitations

3.1. Mesopause excitations by P waves

The LSBB is also equipped with a 3D seismic antenna. Thus the magnetic signals can be permanently compared to the seismic ones. [SQUID]^2 magnetograms have a better resolution than those of magnetic observatories. They frequently exhibit damped wave packets in the absence of any arrival of seismic waves at the LSBB seismic antenna such as those represented in Fig. 5. If one takes into account all the earthquakes with $M_w > 3$, those damped wave packets are delayed by 300 seconds after the emergence out of the ground P wave at the surface. Those 300 seconds comprise the time it takes for the emerging P wave to reach the mesopause. The mesopause is the coldest point above the Earth. As a result it exhibits no day and night altitude variation, hence the constant delay of 300 seconds. The period of the damped oscillations is always in the 60 to 90 seconds range. The mesopause response to P waves is non-linear. The P wave in this case can be assigned to a pulse exciting a mesopause resonance mode. The large resonance period demonstrates that [SQUID]^2 can register mesopause excitations by P waves from very distant earthquakes. From the electromagnetic point of view wherever those earthquakes are taking place on Earth they are always in a near-field situation from the magnetometer. If Rustrel is not in the shadow zone of an earthquake, a second mesopause excitation is also observed 300 seconds after the ground P wave has reached the LSBB [5].

Let us remark that this mechanism does not involve Rayleigh waves: they create a larger displacement of the ground surface. However to a first approximation, the ionospheric response is neutral: as many charged particles are displaced upward than downward since the wave propagation is along the ionosphere and not perpendicular to it as in the case of P waves. It is only for major earthquakes that a magnetic Rayleigh contribution was observed. On the contrary this mesopause resonance mode can be excited by electric fields as the Sichuan–Wenchuan earthquake analysis demonstrates.

3.2. Mesopause excitation by electric field: the Sichuan–Wenchuan precursor May 12, 2008

On May 12, 2008 the daily seismo-magneto graph of LSBB-Rustrel exhibits for the morning the enormous seismic signal from the $M_w = 8.1$ Sichuan–Wenchuan earthquake (Fig. 6, upper traces on the upper part; color code: black = vertical component Z; green = NS; blue = EW).

In the hour before the earthquake the [SQUID]^2 traces filtered between 0.01 and 10 Hz (medium traces, same color code) present a persistent oscillation on horizontal components. Around the initial time of this oscillating regime there has been no quake and during the whole hour only two quakes with $M_w > 3$ happening worldwide.

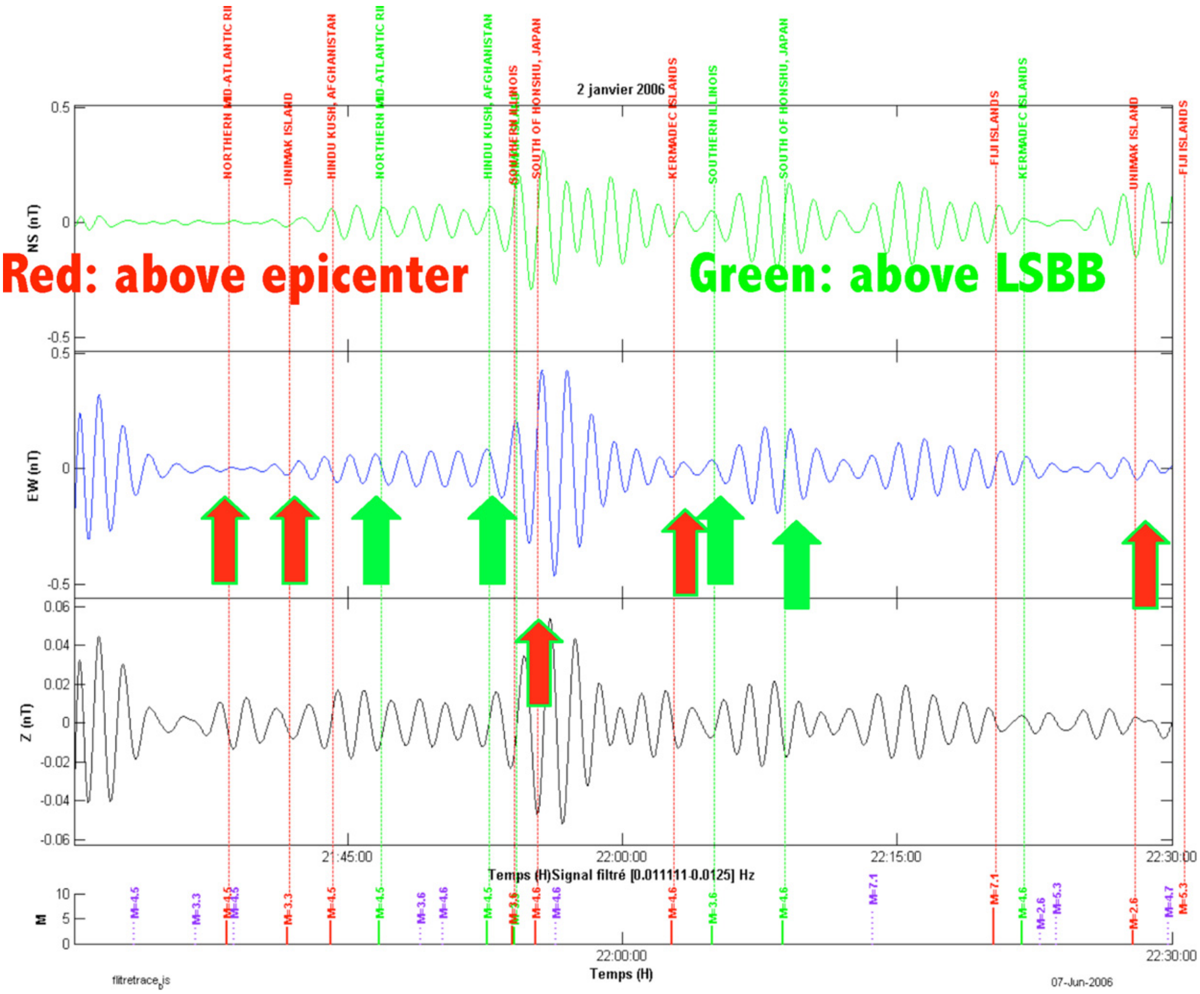

Fig. 5. Filtered [SQUID]^2 signals from 0.0111 to 0.0125 Hz. There are 14 correlations between the arrival time of the P wave at the mesopause with the magnetic response recorded by [SQUID]^2 for worldwide earthquakes with $M_w > 3$ on January 2, 2006 between 21:30 and 22:30 TU. The red arrows correspond to arrival times above each epicenter, the green arrows correspond to arrival times above LSBB-Rustrel if Rustrel was not in the shadow zone.

The dilatation of the time scale of unfiltered raw signals (Fig. 6, lower part) clearly shows on the EW trace (blue) that the oscillations started with a magnetic jump and the same type of jump occurred 30 and 10 minutes before the quake. Those jumps are almost absent from the Z magnetic component meaning that the exciting mechanism was again vertical.

All these features would have remained unnoticed if a few days after the seism, amateur video sequences were not made public on the web. On each of these sequences, shot at a few hundred kilometers from the epicenter, horizontal bands of clouds were visible in which the light was decomposed like a rainbow. Furthermore, those video sequences were in time coincidence with the magnetic jumps (Fig. 7). On the first and third videos, less on the second, beamed structures are also evidence that are compatible with the presence of an electric field.

The oscillating regime of the mesopause vanishes exactly when the epicenter P wave reaches it (the first dotted vertical line from the left indexed 8i in Fig. 8). Furthermore, an electric field presence is confirmed [6] by a magnetic pulse when the P wave of the first replica ($M_w = 6$) reached the mesopause (the second dotted vertical line from the right indexed 6i).

In principle, Fig. 8 contains azimuthal information. However, the NS and EW oscillations do not have constant amplitude. As a result the azimuth unfolding could not be strictly rigorous. Taking only into account for the azimuth the linear envelopes of wave packets almost constants for a few minutes one obtains a set of azimuth values around $35 \pm 10°$. Since this is a near-field situation this azimuth does not indicate an angle of propagation but the source polarization at its origin. This naïve procedure has been done in the total absence of information about the earthquake ground movements. The 2008 AGU Fall Meeting has given the opportunity to learn that the earthquake has created a fault line over a few hundreds of kilometers, oriented 35° East (Fig. 9) (http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/2008ryan/). Because of the very crude unfolding procedure what is important here is not the qualitative numerical agreement but rather the

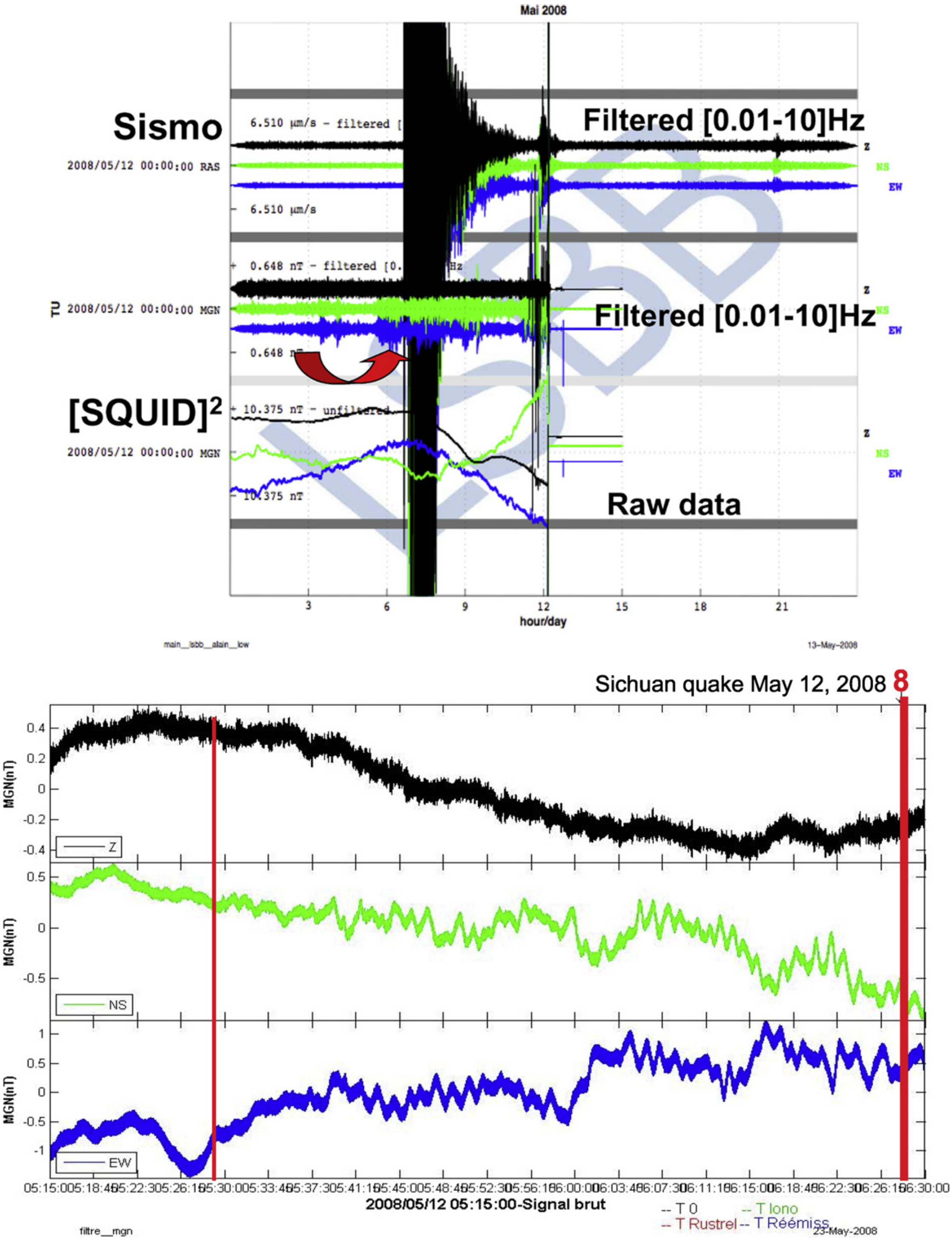

Fig. 6. Upper part: standard LSBB full day recording of the seismic (upper traces denoted RAS) and magnetic signals (lower traces MGN) both filtered [0.01–10] Hz, lower traces denoted MGN: raw magnetometer signals. Lower part: time dilatation of the raw unfiltered magnetic signals in the hour before the earthquake. On EW (blue trace) it is apparent that the beginning of the oscillations (black arrow) is superposed to a magnetic "jump". Two other jumps are visible 30 and 10 minutes before the quake.

verification that in these cases, whether the excitation mechanism is via electric field or P wave, one gets the polarization source. The large length of the fault line explains also incidentally why the rainbow clouds have been observed so far from the epicenter, since the electric field lines are of the same scale length.

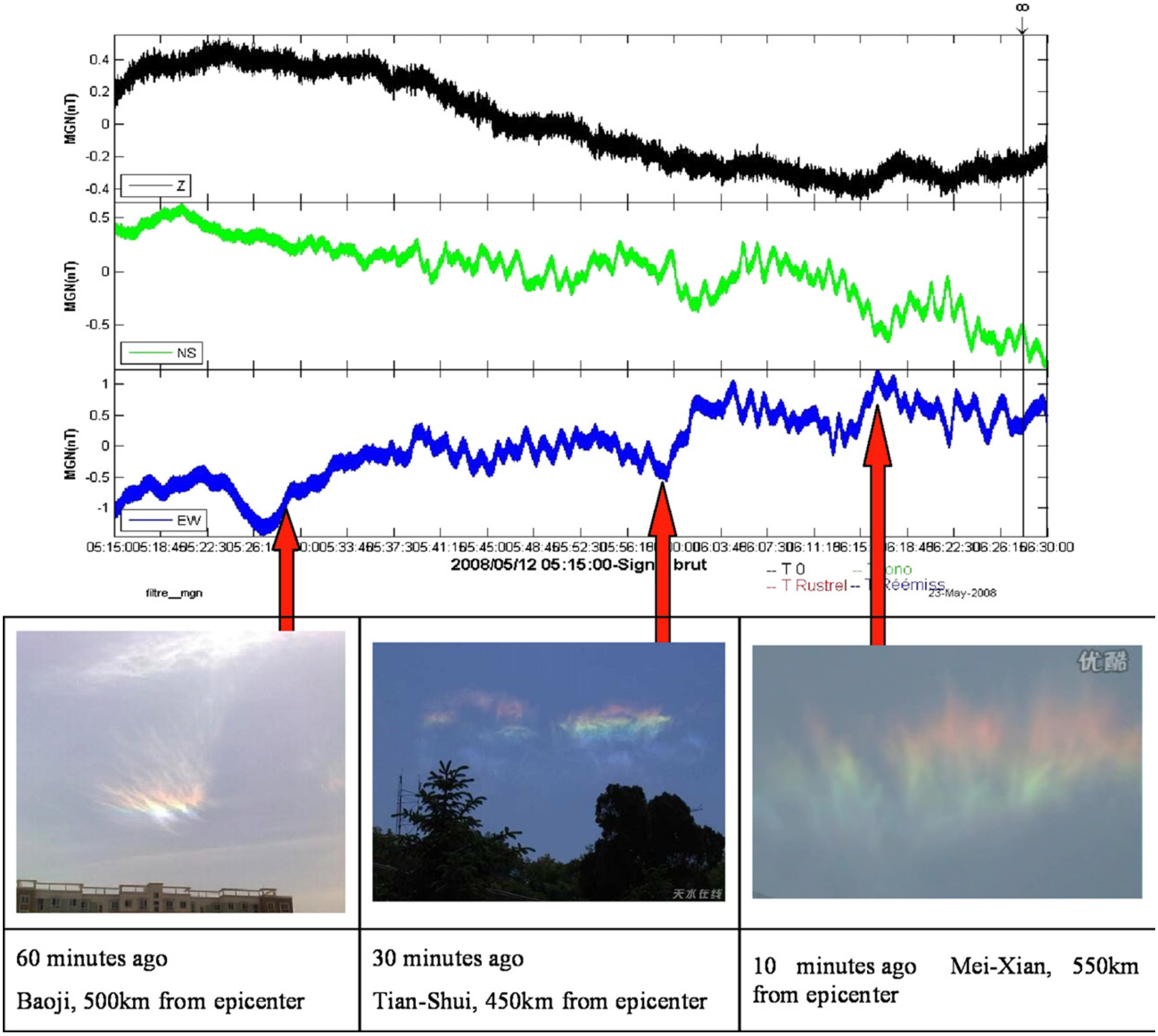

Fig. 7. "Rainbow clouds" registered by video each time at a few hundred kilometers from the future epicenter were in time coincidence with magnetic jumps. A beamed structure is also clearly visible on the first and third videos, less on the second, compatible with the presence of an electric field.

4. Ionosphere response to the Earth normal modes

Because of their limited sensitivity conventional seismometer networks detect Earth normal modes of oscillations only for earthquakes $M_w > 8$. Having higher sensitivity superconducting gravimeters, has created the possibility of extending the observation of these modes to the first ones whether they are spherical (S modes) or toroidal (T modes) for 72 hours of seismic calm ($M_w > 5.7$) [7]. The evaluation of the possibilities offered by ionosphere responses relies on the study of the minimum noise level in the frequency range of interest between 1 to 3 millihertz. A period of 72 hours of magnetic calm (all earthquakes with $M_w < 5.5$ and quiet space weather) has been selected (Fig. 10) and studied by Fourier spectrum analysis (Fig. 11). On the 3 components the Fourier spectrum is above the $1/f$ curve.

The Z component is much weaker, which means that the signal sources are essentially generated by vertical displacements of electric charges. A better time resolution of this Fourier graph reveals that this signal in excess of $1/f$ is a multitude of lines which makes it appear like a noise spectrum. To be sure that it is not an artifact various sampling rates have been used and a smoothing over five consecutive points of the spectrum for each sampling rate to verify that the lines are stable with respect to data sampling and smoothing.

The physical meaning of a fraction of these peaks is clear if one compares the spectrum to the PREM model [8] of the Earth normal modes. Some of the results are shown in Fig. 12. All the indexed peaks correspond, with a precision better than 1%, to a normal mode of the Earth from the PREM model [9]. In other terms the Earth–ionosphere interaction in this case preserves these excitation frequencies. At these quasi-static regimes the ionosphere response is a global vertical

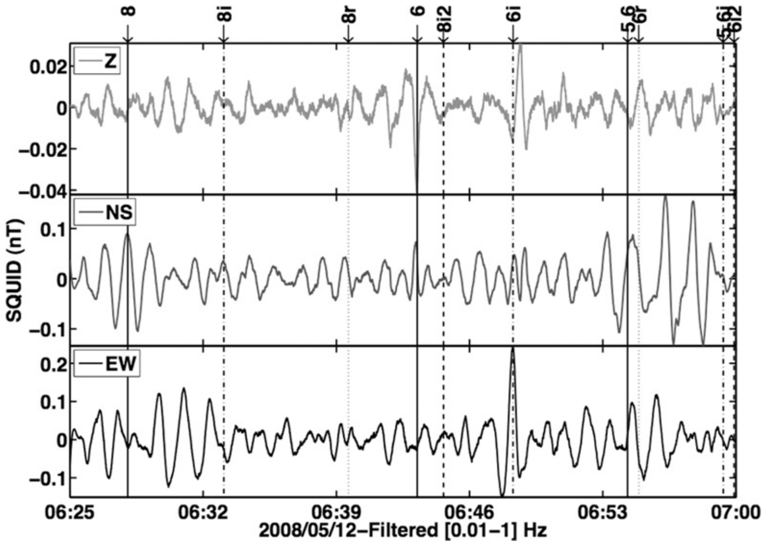

Fig. 8. Extinction of the mesopause resonance mode of the Sichuan–Wenchuan earthquake at the arrival of the quake P wave at the mesopause 300 seconds after the quake (the first dotted vertical line from the left indexed 8i). The presence of electric field effects is revealed by the emission of a first magnetic pulse (Z and NS) at the first aftershock ($M_w = 6$) and a second one when the corresponding P wave of this aftershock reaches the mesopause (vertical line indexed 6i).

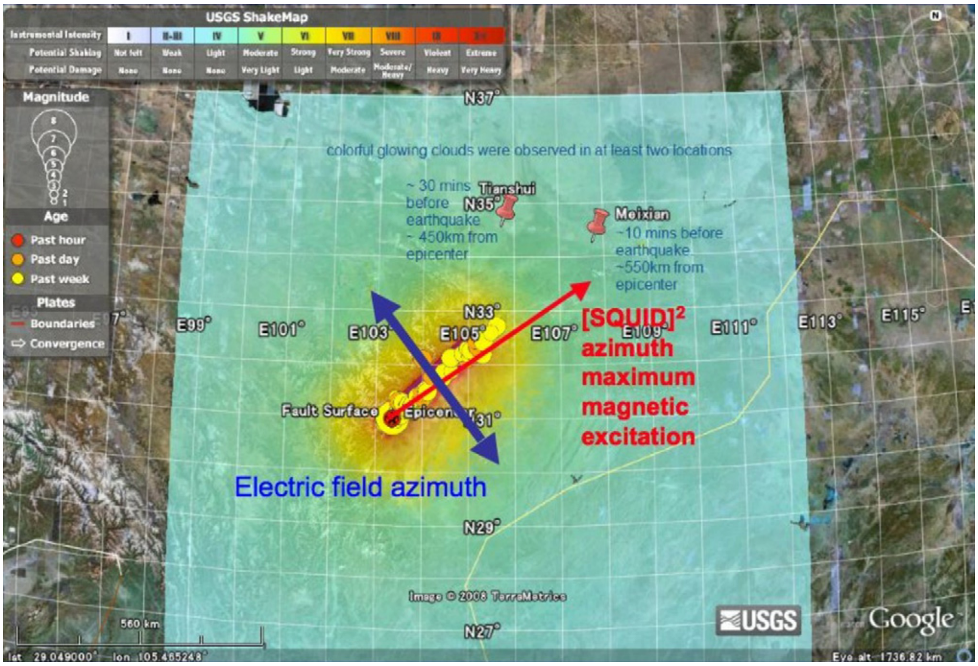

Fig. 9. Fault line of the Sichuan–Wenchuan earthquake and rough azimuth unfolding of the [SQUID]^2 signals. The red pins indicate two of the three sites where the "rainbow clouds" due to electric fields were observed. The length of the fault line explains why they were observed so far from the epicenter.

translation above the area related to a given normal mode. [SQUID]^2 detects the Earth normal modes in quiet conditions, even in the absence of major seisms. The PREM model does not identify all the spectrum lines. The interpretation of the unidentified lines is an ongoing work.

5. Magnetic storms and sprites

5.1. Magnetic storms

The magnetic detection of magnetic storms has never been a question of sensitivity because of the large magnetic perturbations caused by magnetic storms. However, a low level of environmental noise allows the full exploitation of the

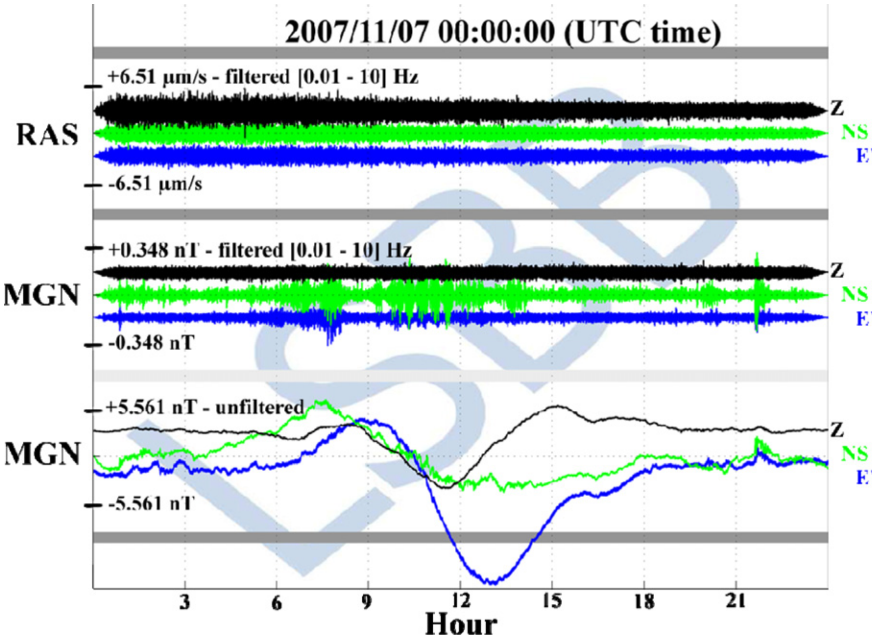

Fig. 10. Magnetogram of a quiet day (MGN traces).

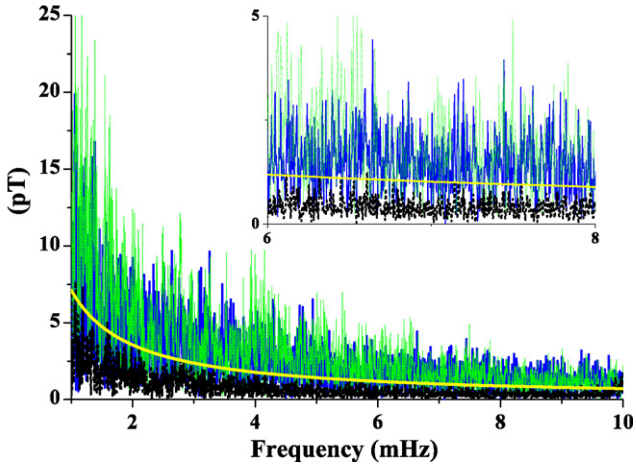

Fig. 11. Fourier spectrum of the 3 components. On each of them the signal level is above the $1/f$ curve (yellow).

SQUID sensitivity. The signals obtained are the worldwide response of the Earth magnetic field to the magnetic storm. In spite of the fact that $[\text{SQUID}]^2$ is at mid latitude, these recorded signals include the very large Polar fluctuations. This is what is shown in Fig. 13 which compares the recording magnetometers from the IMAGE network (Scandinavian conventional magnetometers) by order of decreasing latitude to the $[\text{SQUID}]^2$ recording of the magnetic storm of December 14, 2006.

5.2. Sprites

A strong thunderstorm occurred on September 2, 2009 over the *Golfe du Lion* with lot of lightning strokes. Ten of these electric flashes gave birth to sprites (Transient Luminous Events). Those TLE were recorded optically by an ultra-sensible camera in operation at the Pic du Midi Observatory, about 300 km W–WN from the center of the thunderstorm and at $[\text{SQUID}]^2$ 150 km from the thunderstorm center in the E–EN direction. (See Fig. 14.)

For each of these TLE the $[\text{SQUID}]^2$ system has recorded characteristic unipolar magnetic pulses which are indeed the low frequency tail of the lightning stroke generating the TLE. Preliminary unfolding in collaboration with Serge Soula (*Laboratoire d'Aérologie Toulouse*) has confirmed the time coincidence for the whole set.

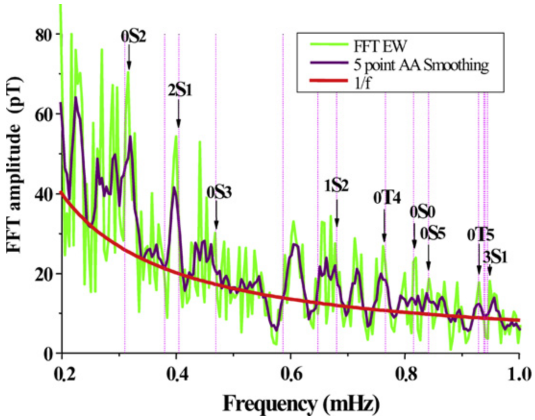

Fig. 12. Spectra of some ionosphere responses compared to the normal modes of the Earth. The indexed peaks are within 1% of the frequency of the corresponding normal mode in the PREM model.

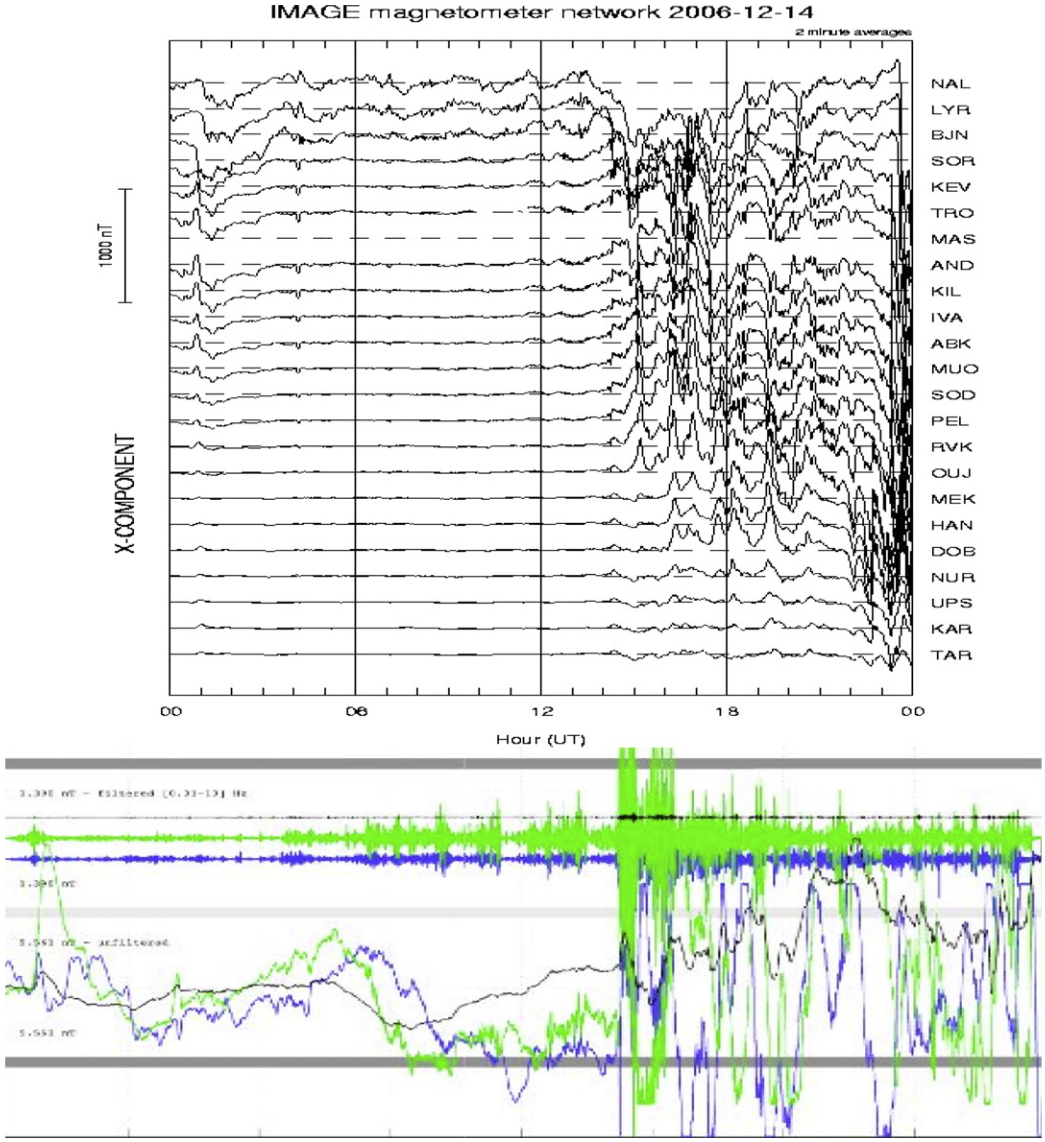

Fig. 13. Upper curves: IMAGE network magnetic observatories full day recordings by decreasing latitude (from 78.92 down to 66.90) compared to the [SQUID]^2 signals for the magnetic storm of December 14, 2006. (Thanks to Michel Parrot, LPCE Orléans.)

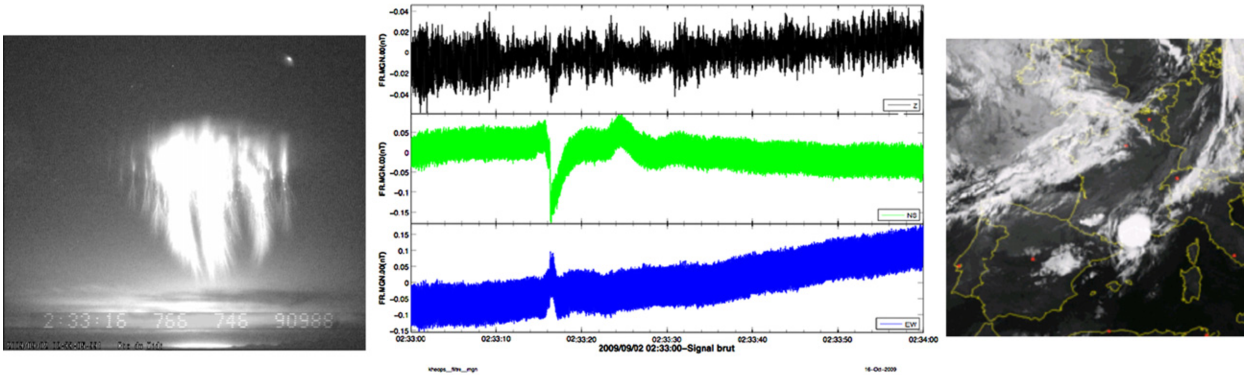

Fig. 14. Observation of a TLE on September 2, 2009 at 02:33:16 TU by an ultra-sensible camera at the Pic du Midi Observatory 300 km W–WN from the thunderstorm center (picture Meteosat on the right) and its time recording by [SQUID]^2 at 150 km E–EN. The magnetic pulse is almost horizontal, which indicates that the corresponding lightning stroke is vertical. The recording covers sixty seconds from 02:33 to 02:34.

6. Conclusion

Those results illustrate that a highly sensitive magnetometer in a low-noise environment is a new tool for the study of Earth–ionosphere interactions. For the time being [SQUID]^2 is the only system of this kind in operation. A worldwide network of at least a few stations of this type, even with slightly reduced low-noise characteristics but in time coincidence with [SQUID]^2 would be a step in the right direction. Preliminary contacts for the creation of such a network have already begun [10].

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