LIPAC & LIBS: A HAPPY MARRIAGE

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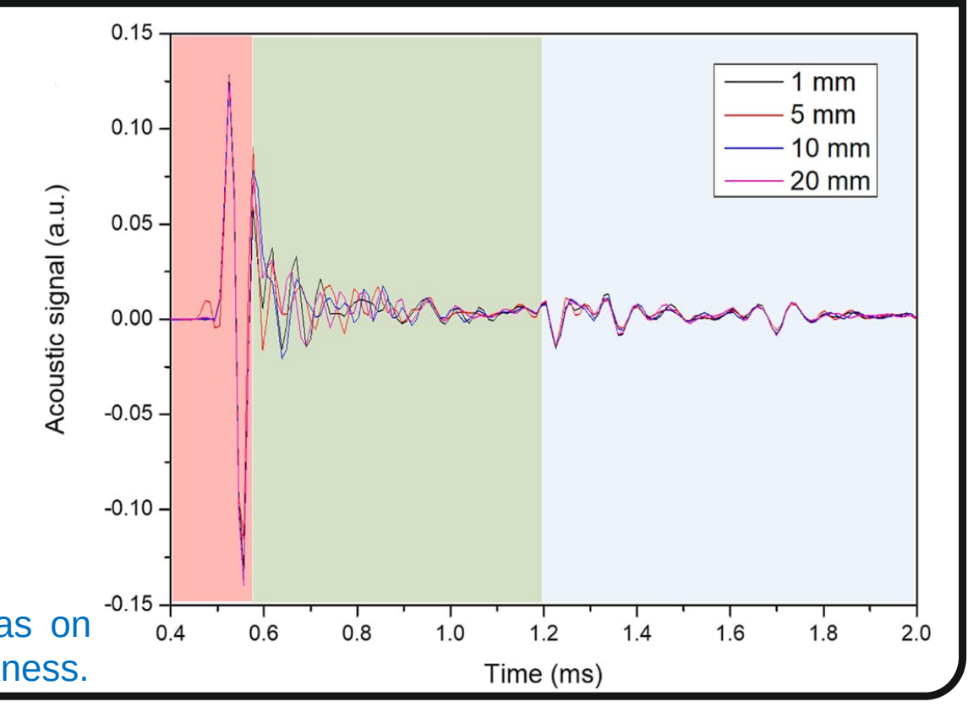
1. ABSTRACT

Plasma formation by focused high-power and short laser pulses on matter is always accompanied by a characteristic snapping sound. Precedents on laser-generated acoustic transients are not numerous in literature specially when compared to other laser-produced phenomena. However, its promising uses have led it to an interesting issue to explore. Thus, particularities guiding and conditioning the acoustic response are being deeply scrutinized towards a better exploitation of this asset either when deployed independently or when combined with LIBS to synergistically improve its capabilities.

2. THE LIPAC SIGNAL

Three distinctive sections identified within the sound wave: A first segment intimately associated to the singular laser-matter coupling. Two later segments reflecting the dynamics of the laser-impacted surface, and the influence of the surrounding terrain where analysis is performed, with a relevant presence of echoes and reflections.



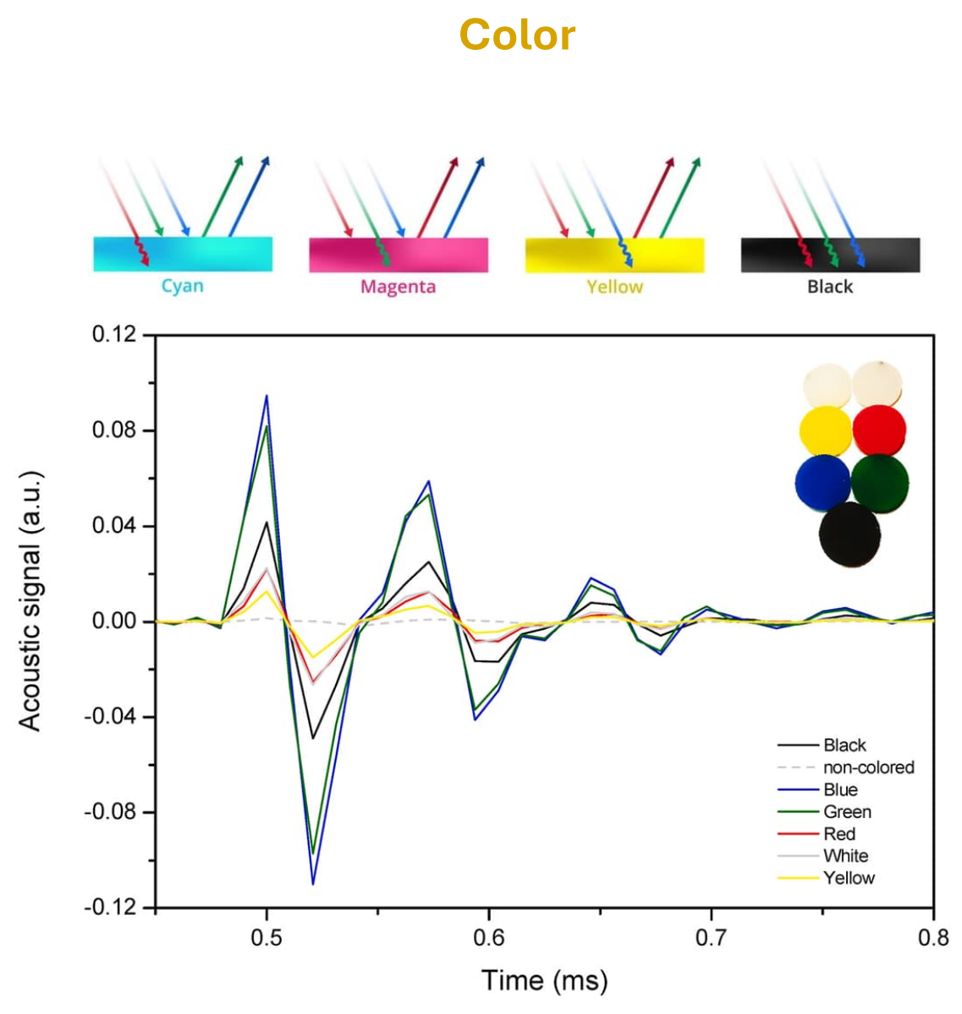
Sections featured during the sound wave lifetime from plasmas on solid aluminum cylinders of 30 mm in diameter and variable thickness.

3. KNOW-HOW ON LIPAC

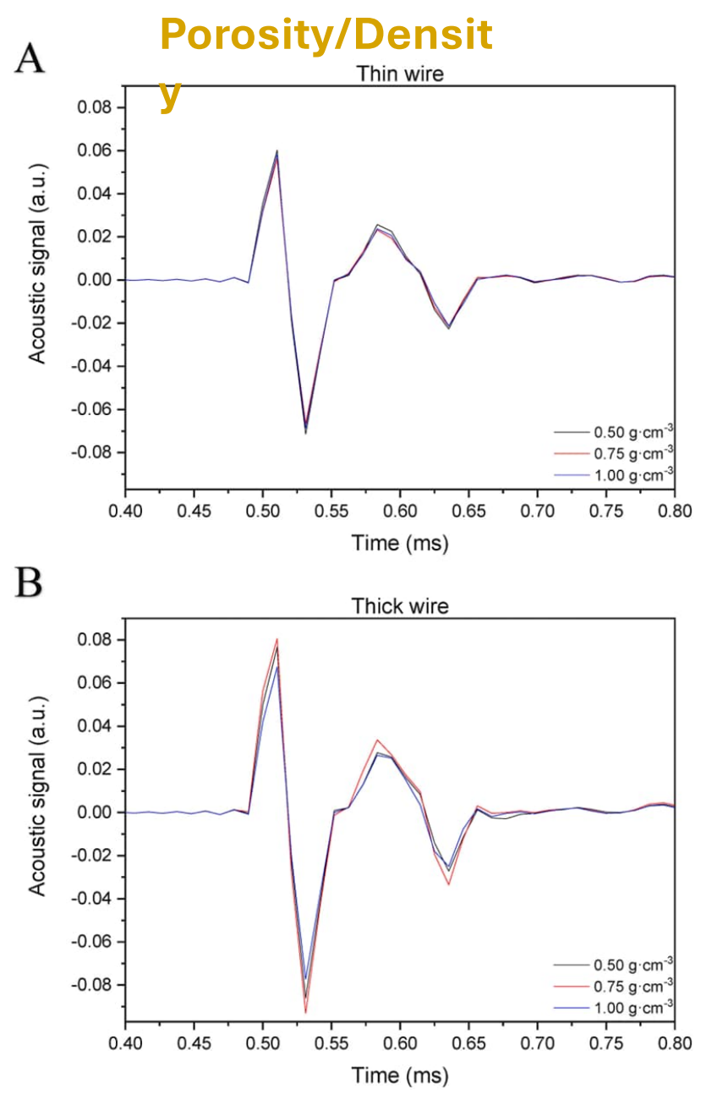
The absolute deviation for the most sensitive oscillation ─*named the peak-to-peak amplitude*─ of the sound wave is considered the most significant asset to score the plasma acoustics.

Impact of Sample-Related Factors

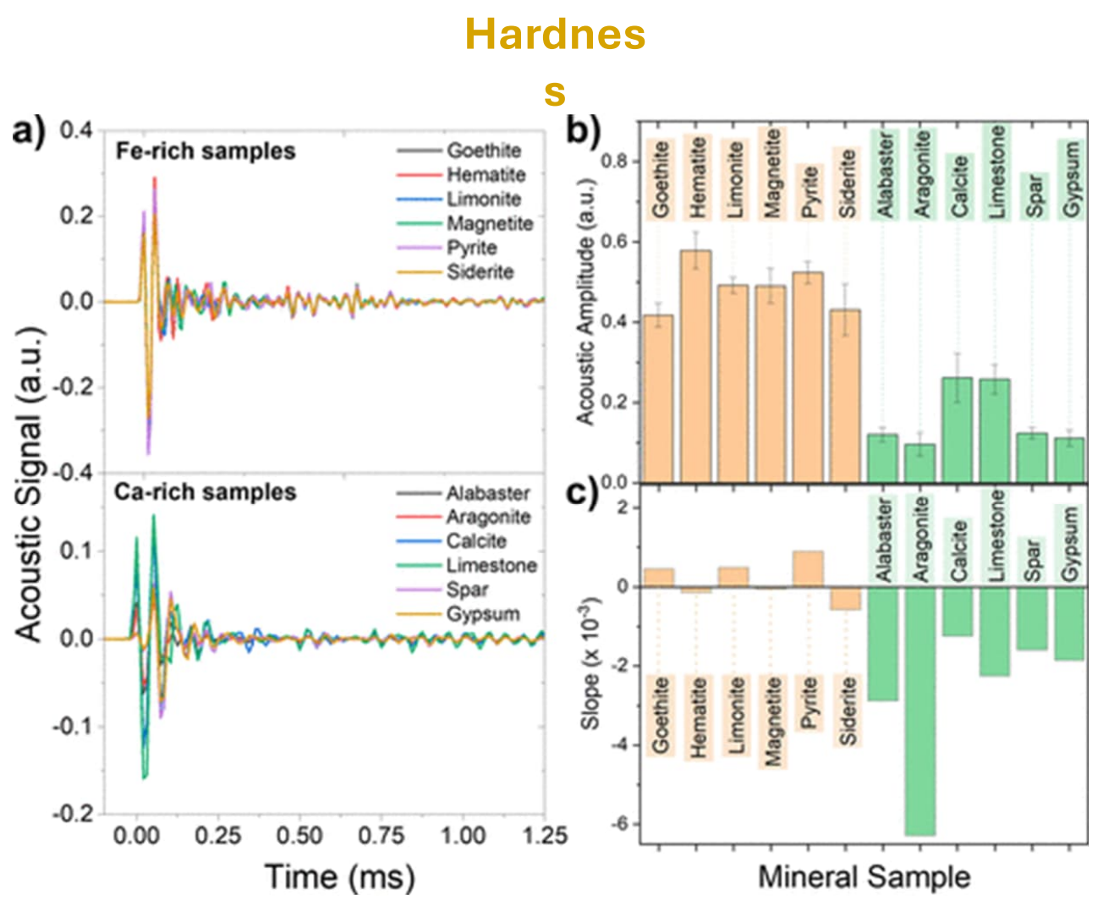
The physical traits of the material guide the magnitude of the main N-peak amplitude in the sound wave



Acoustic waves for plasmaphonies coming from colored epoxy cylinders.



Acoustic waves for plasmaphonies coming from *3D*-printed cylinders from thin (A) and thick (B) wires, respectively.



(a) Average time domain signals in the 0.1–1.25 ms range for a pair sets of minerals hard and soft on the Mohs scale.

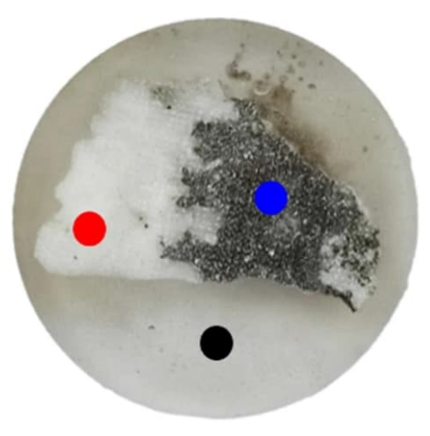
(b) Average amplitude in the first maximum of the acoustic wave for each mineral studied.

(c) Slope value for variation of acoustic amplitude during a successive laser shot series. Values close to 0 indicated stable acoustic response while negative values reflect decreasing in the measured sound intensity.

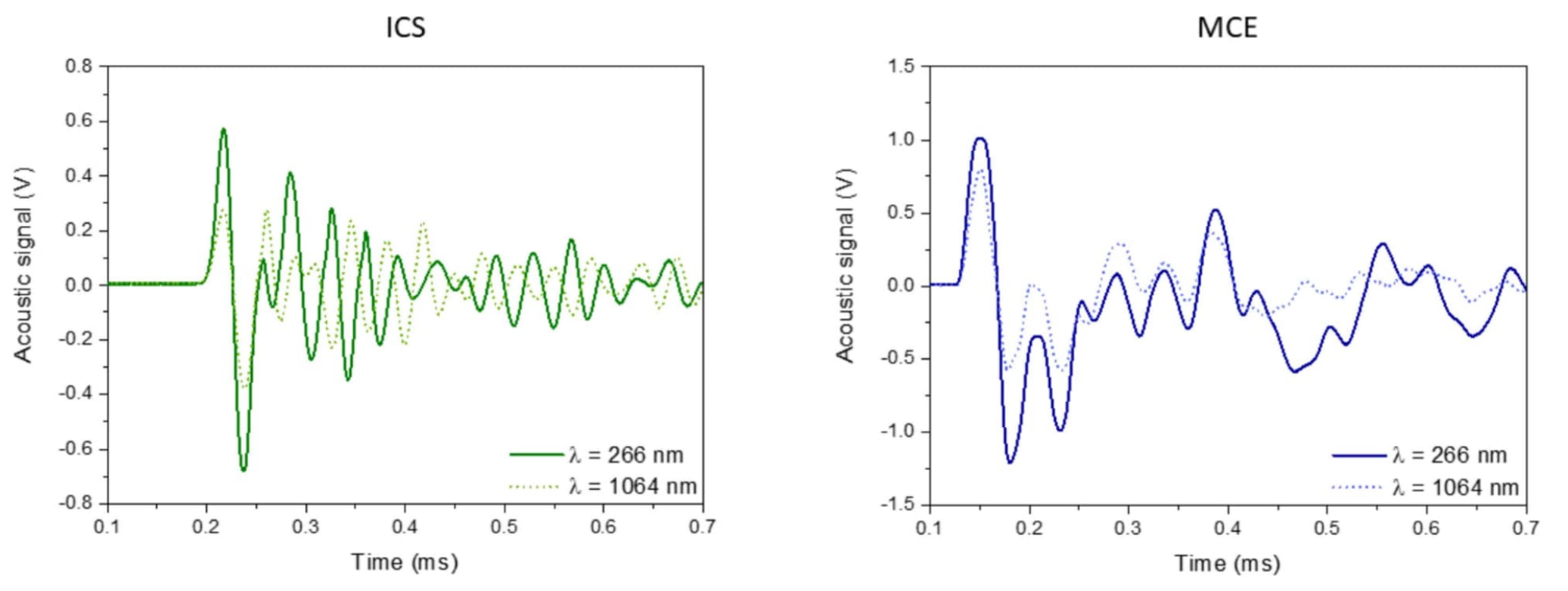
Impact of Instrumental Factors

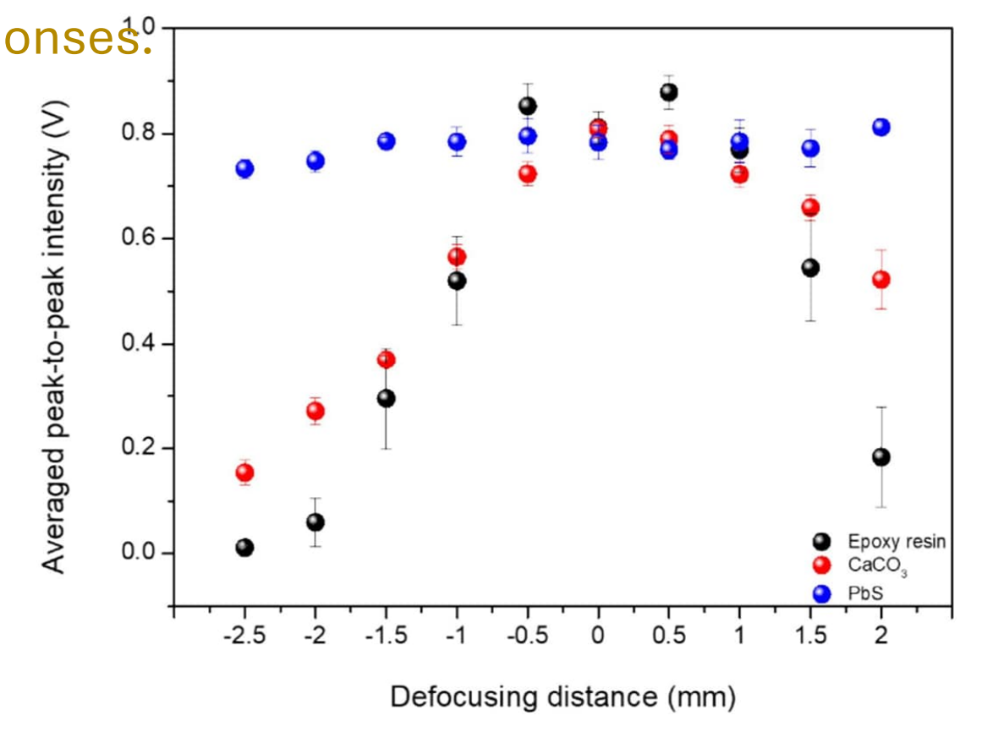
Variables like laser pulse wavelength (λ) and fluence also govern the magnitude of the main N-peak amplitude in the sound wave

The more the excitation parameters exceed the ablation threshold of the materials the higher the similarity between their acoustic responses.



Averaged acoustic signals for plasmas generated on aluminum samples using different excitation wavelengths and recorded using different microphones.

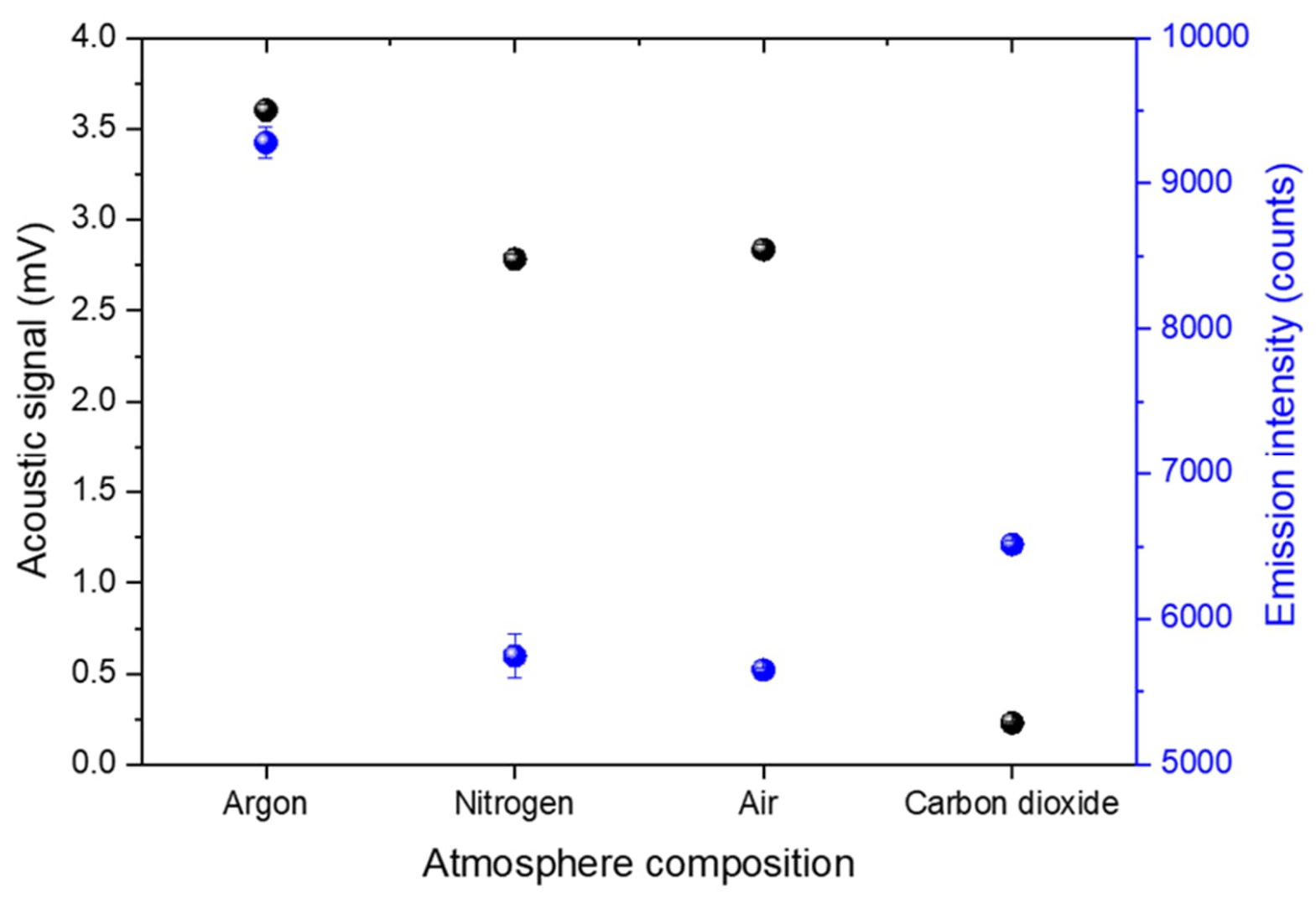




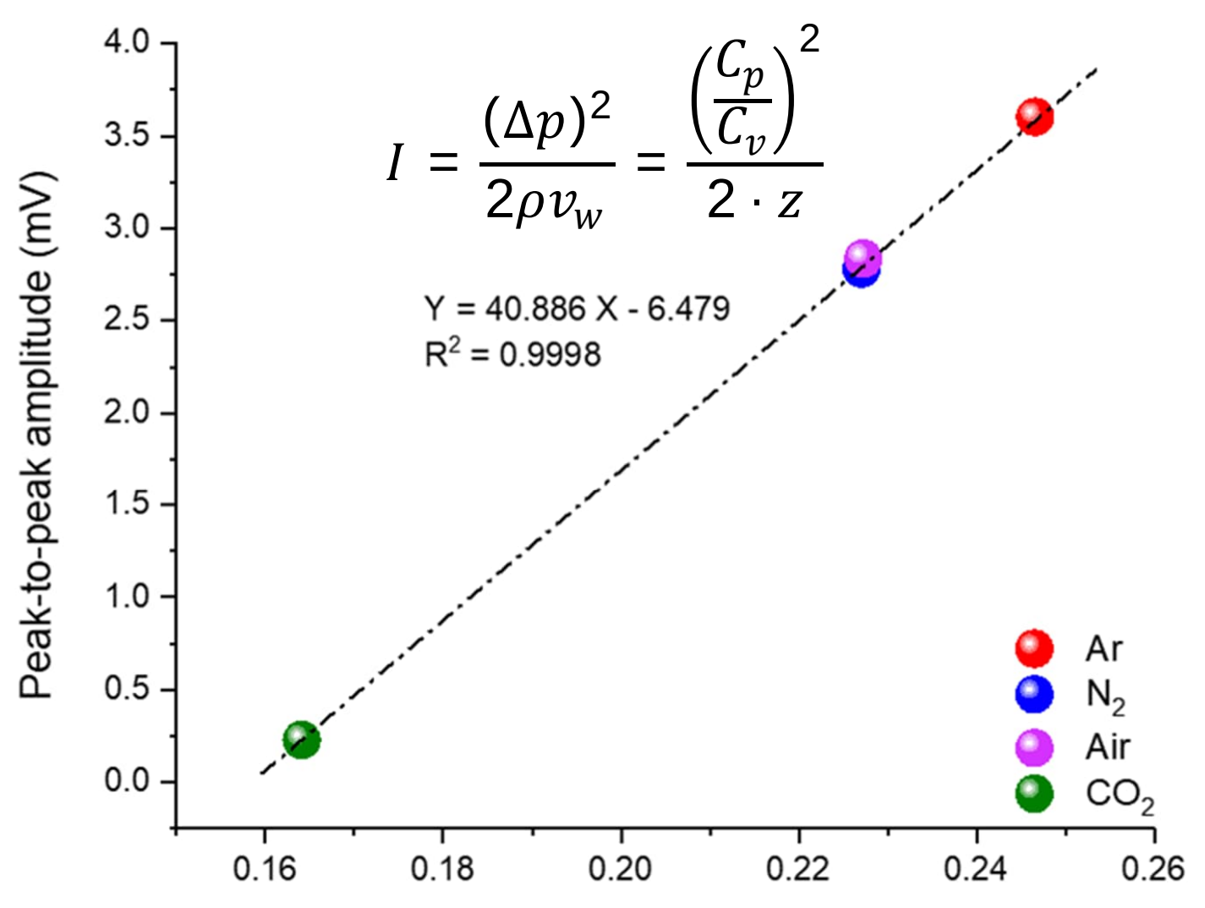
Variations in the averaged (n = 75) first peak-to-peak amplitudes of the acoustic signals from plasmas generated at separate points in three well-differentiated areas recorded by the ICS microphone shown as a function of the laser defocusing distance.

Impact of Atmosphere Factors

The sensitivity of the acoustic response differs for differently composed atmospheres. A close relationship between the acoustic intensity and the ratio of the adiabatic index to the acoustic impedance of the gas surrounding the plasma along its complete process is revealed.



Averaged scores (with their associated Root Mean Square -RMS- variability) for LIPAc and LIBS concurrent responses from 300 plasma events produced by laser shots on an aluminum cylinder as a function of the chemical composition of the surrounding atmosphere; all them at constant both the pressure (10 mbar) and the temperature (-20 °C).

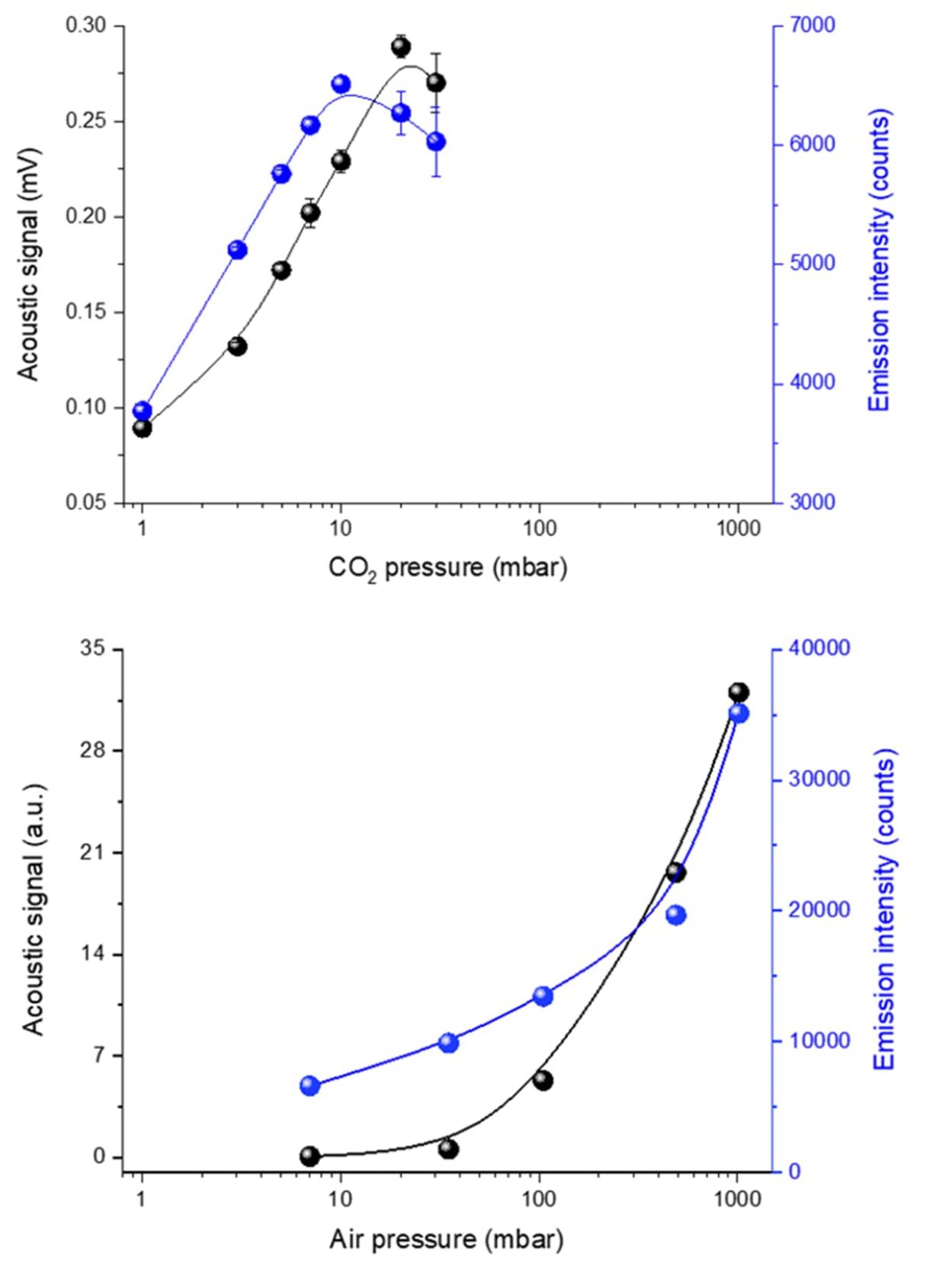


$$I = \frac{(\Delta p)^2}{2\rho v_w} = \frac{\left(\frac{C_p}{C_v}\right)^2}{2 \cdot z}$$

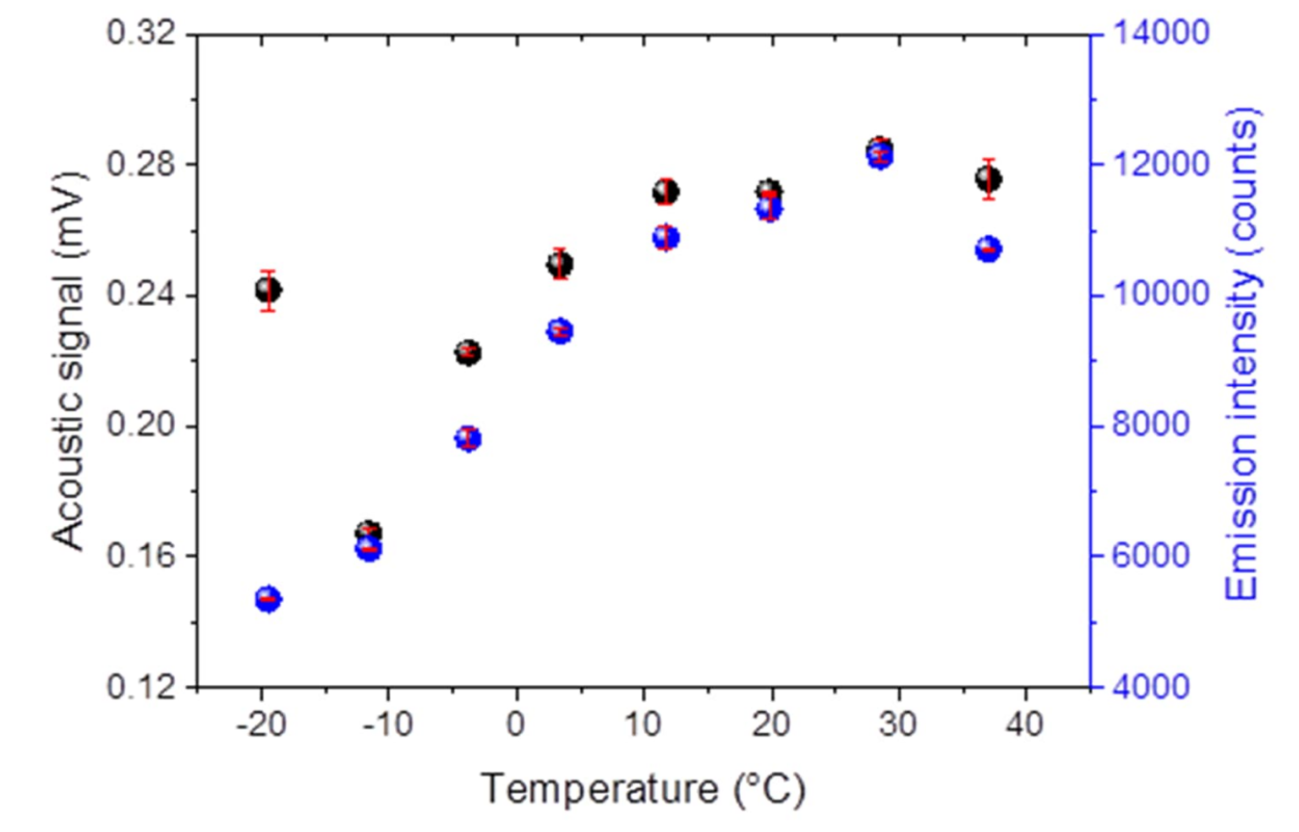
Y = 40.886 X - 6.479
$R^2 = 0.9998$

Correlation of empirical vs. theoretical values for the acoustic intensity under differently chemical composed atmospheres when are set at 10 mbar pressure and -20 °C temperature.

The correspondence between optic and acoustic emissions of plasmas for the variations on pressure and temperature of the atmosphere suggests that such variables singularize the features of the plasma to be created rather than to condition the ongoing plasma sound itself.



Comparison of the isothermal curves for the LIBS-LIPACs dual responses of laser-produced plasmas under different atmospheres, CO_2 at -20˚C and air at 25˚C, from an aluminum foil and a pyrite fragment, respectively.

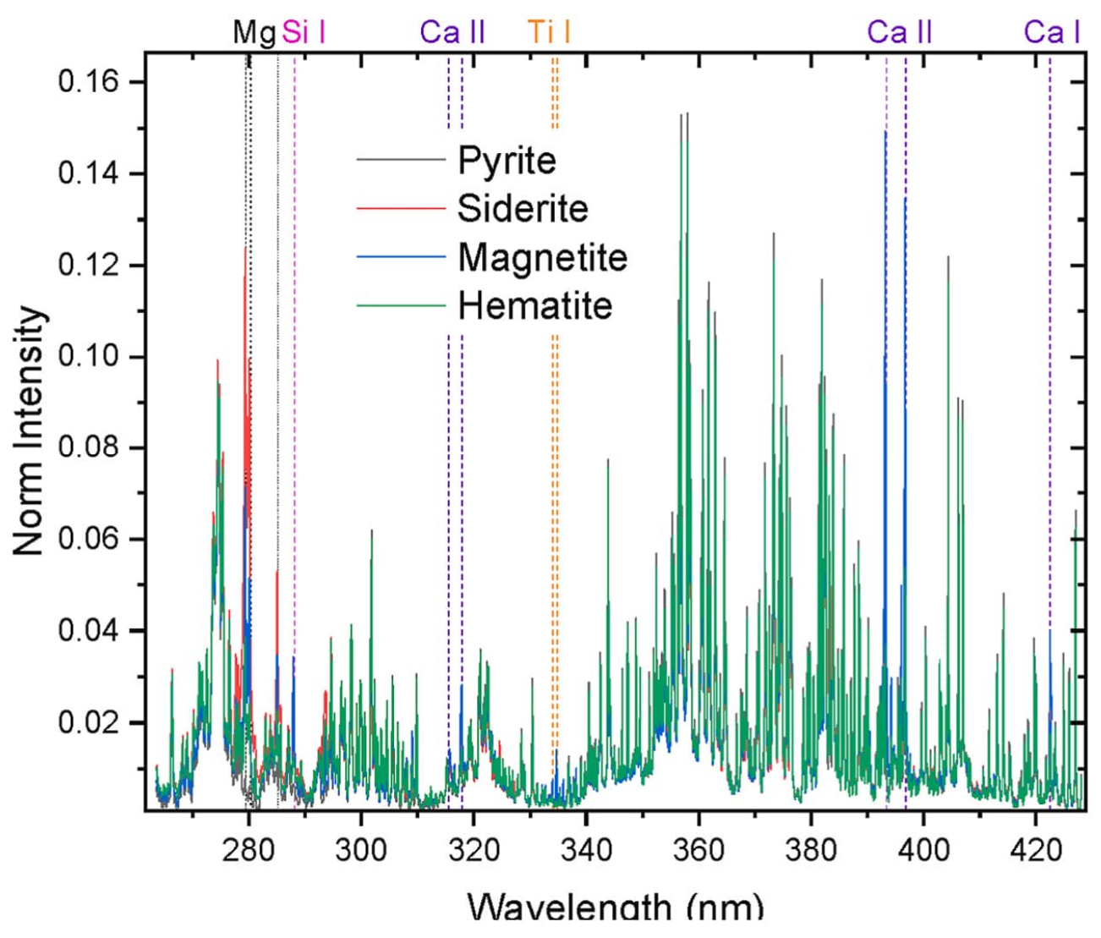


Evolution of scores (with their associated Root Mean Square -RMS- variability) for LIPAc and LIBS concurrent responses from 300 plasma events produced by laser shots on an Al cylinder under a CO_2 surrounding atmosphere at 10 mbar pressure, as a function of changing temperature in the range spanning from -20 °C to 40 °C.

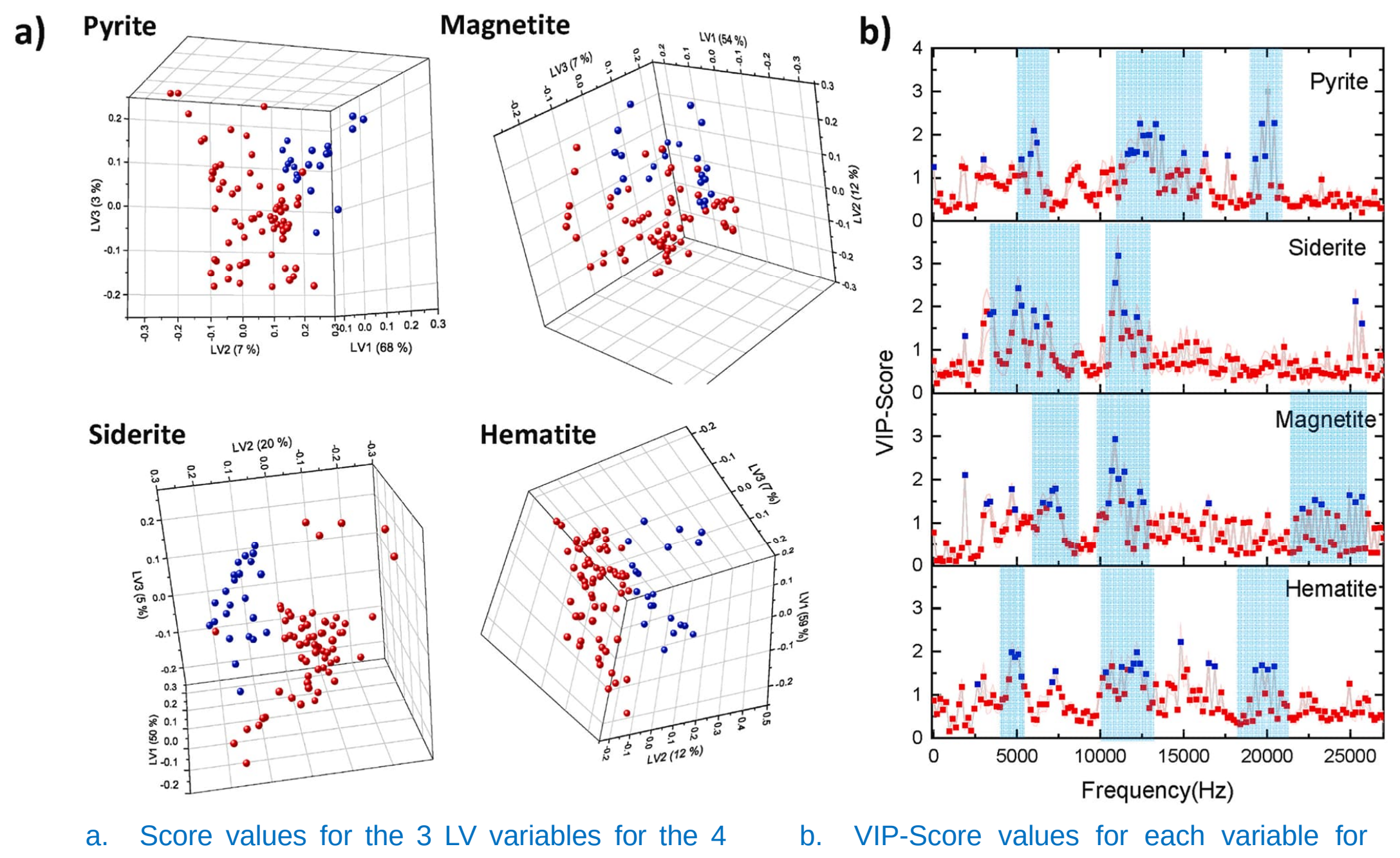
4. RELIABLE APPLICABILITY OF LIPAC

Differentiation of Closely Related Mineral Phases

Acoustic spectra of plasmas in the frequency domain provide additional assets for a better differentiation of specimens when the acquired LIBS spectra predominantly feature almost the same emission lines.



LIBS spectra of four different Fe-based mineral phases with non-Fe elemental lines highlighted.



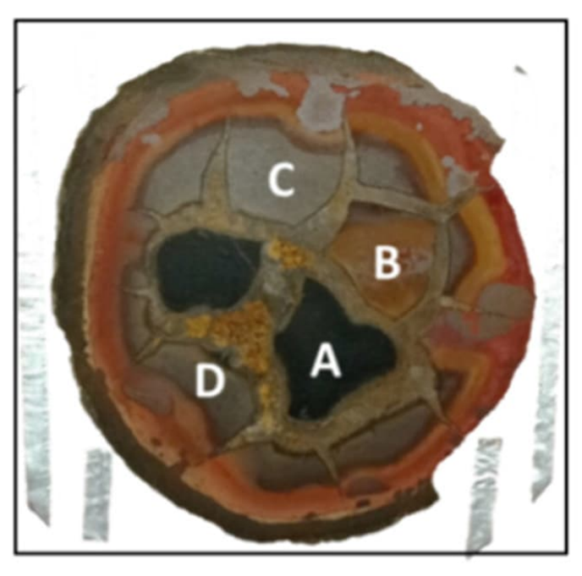
a. Score values for the 3 LV variables for the 4 PLS one-vs-all models. Blue dots represent the +1 phase for each model.

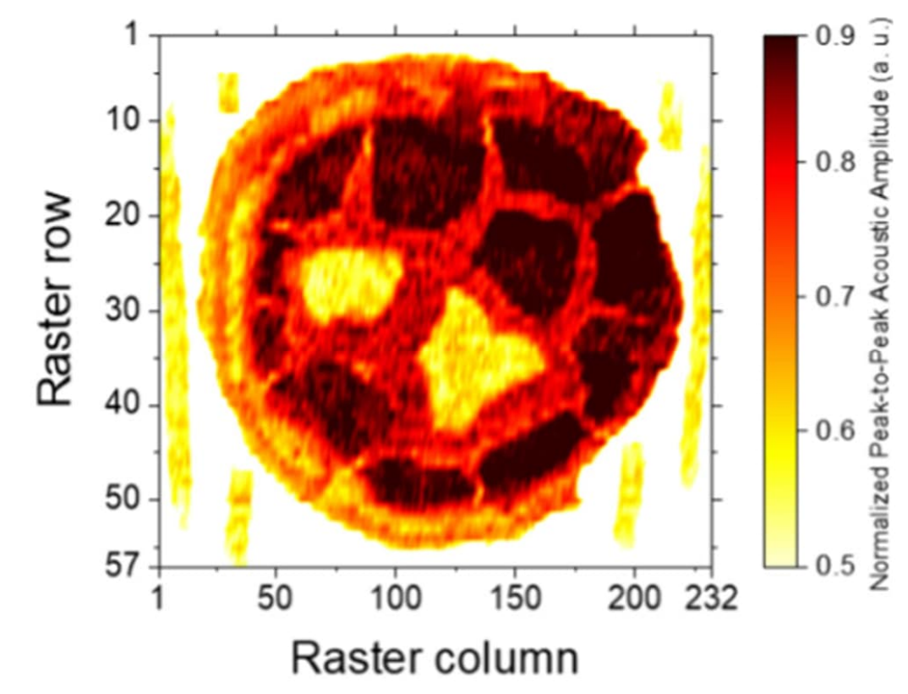
b. VIP-Score values for each variable for the 4 PLS models. Blue dots represent the variables above the cutoff threshold.

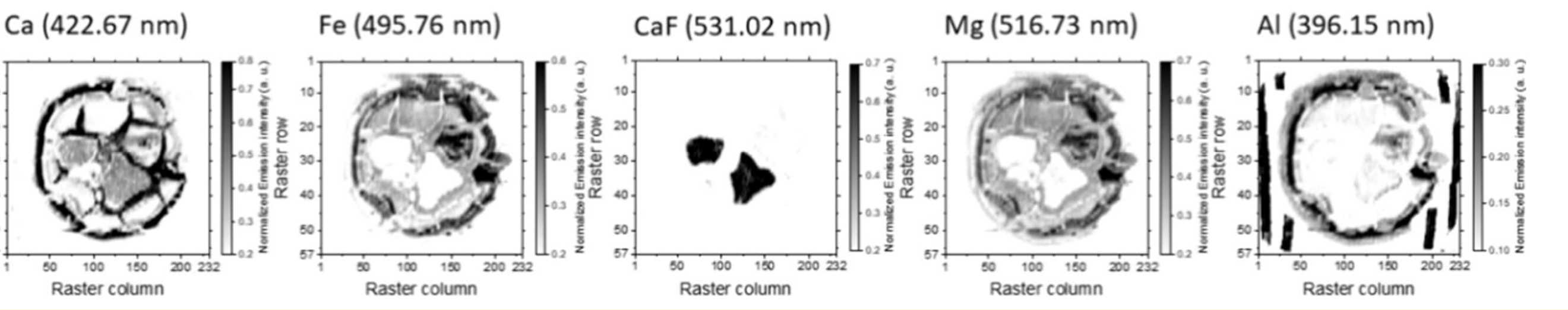
Mixed-Mapping of Geological Materials

By harmonizing characteristic scores of concurrent LIBS and LIPAC responses of laser plasmas from the surface of a geological specimen, categorization of mineral phases composing the hosting rock is improved.

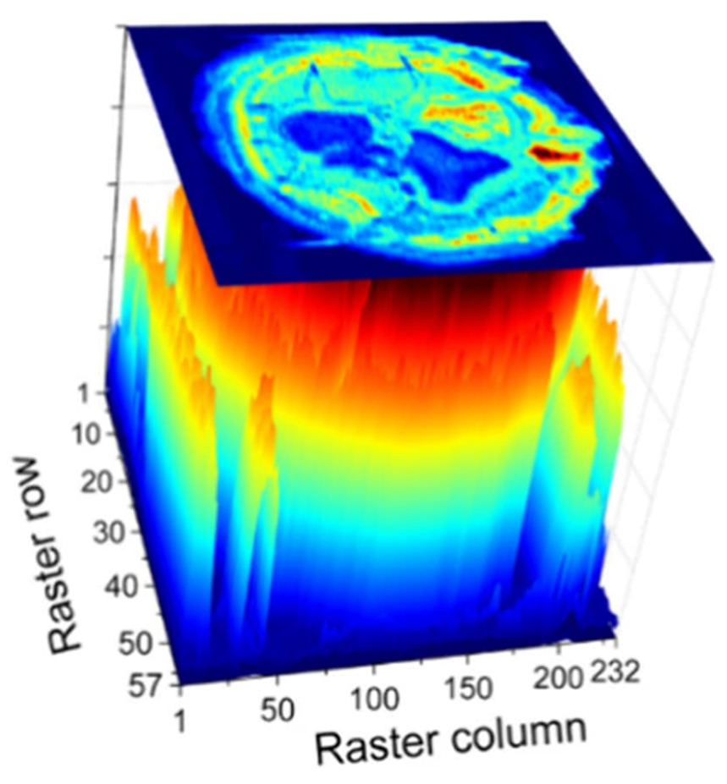
Acoustic map (top) and elemental distribution maps (down, at 1:2 scale) of Ca (422.67 nm), Fe (438.32 nm), F (monitored by CaF bands located at 529–540 nm), Mg (516.73 nm), and Al (396.15 nm), normalized all, built from LIPAc and LIBS responses of plasmas induced over the surface of a septarian nodule. Distinctive polygonal blocks cataloged as A–D are labeled.



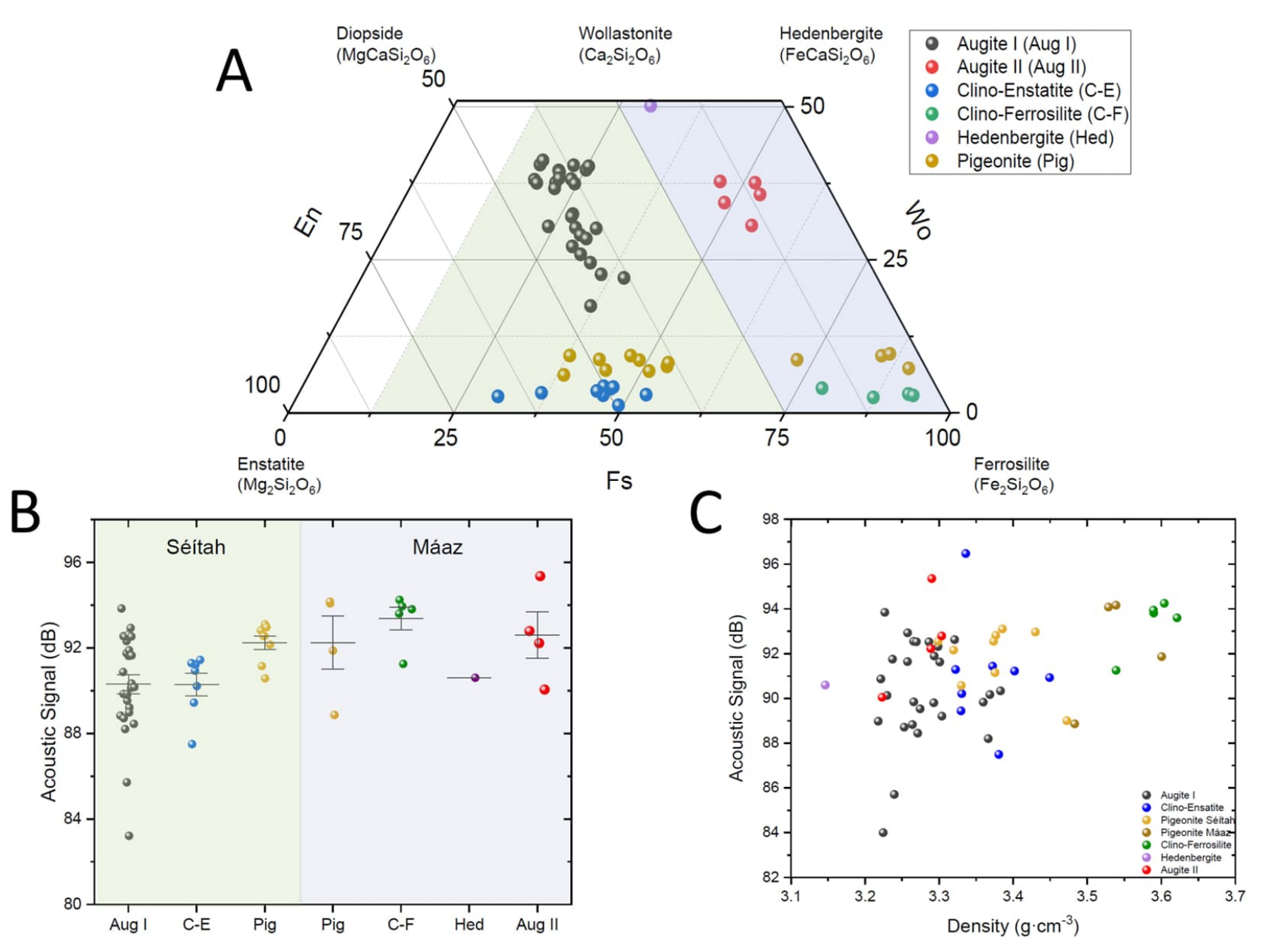




Spectral data polyhedron resulting from the stacking of the ″monoelemental″ chemical distribution maps and the acoustic map.



Sound of Geological Targets on Mars



The acoustic responses emerged along LIBS analysis of multiple geological targets carried out on the first 380 Sols of the Mars2020 mission at Jezero crater, Mars, revealed that the harder the surface and more compact the geological material, the louder and more stable the acoustic signal of the produced plasmas.

A) Pyroxene quadrilateral including stoichiometric pyroxene (indicated as follows: Wo, wollastonite; En, enstatite; and Fs, ferrosilite) of the studied targets identified at Séítah and Máaz geological formations in Mars.

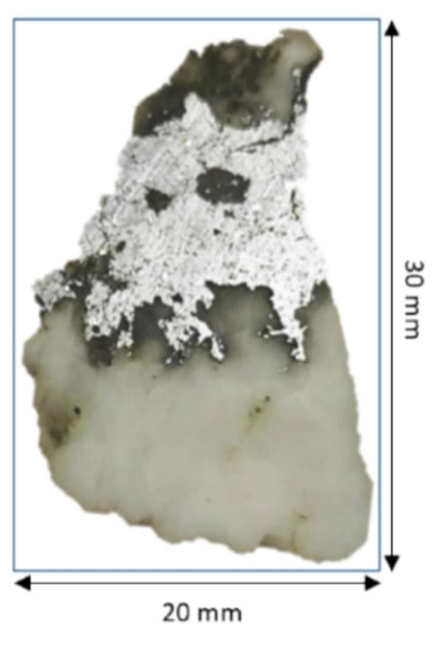
B) Distribution and averaged acoustic signal (black line) for the pyroxenes observed at Séítah and Máaz geological formations in Mars.

C) Evolution of the acoustic signal according the calculated target density.

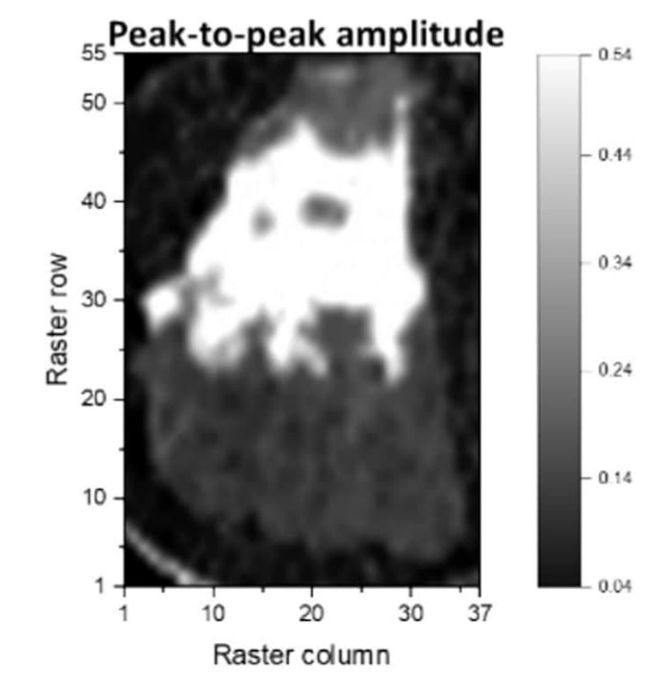
Overcoming the Matrix Effect in LIBS

LIBS scores corrected from the acoustic asset of plasma has proved suppress the discrepancies between the atomic and ionic emission lines.

Galena specimen

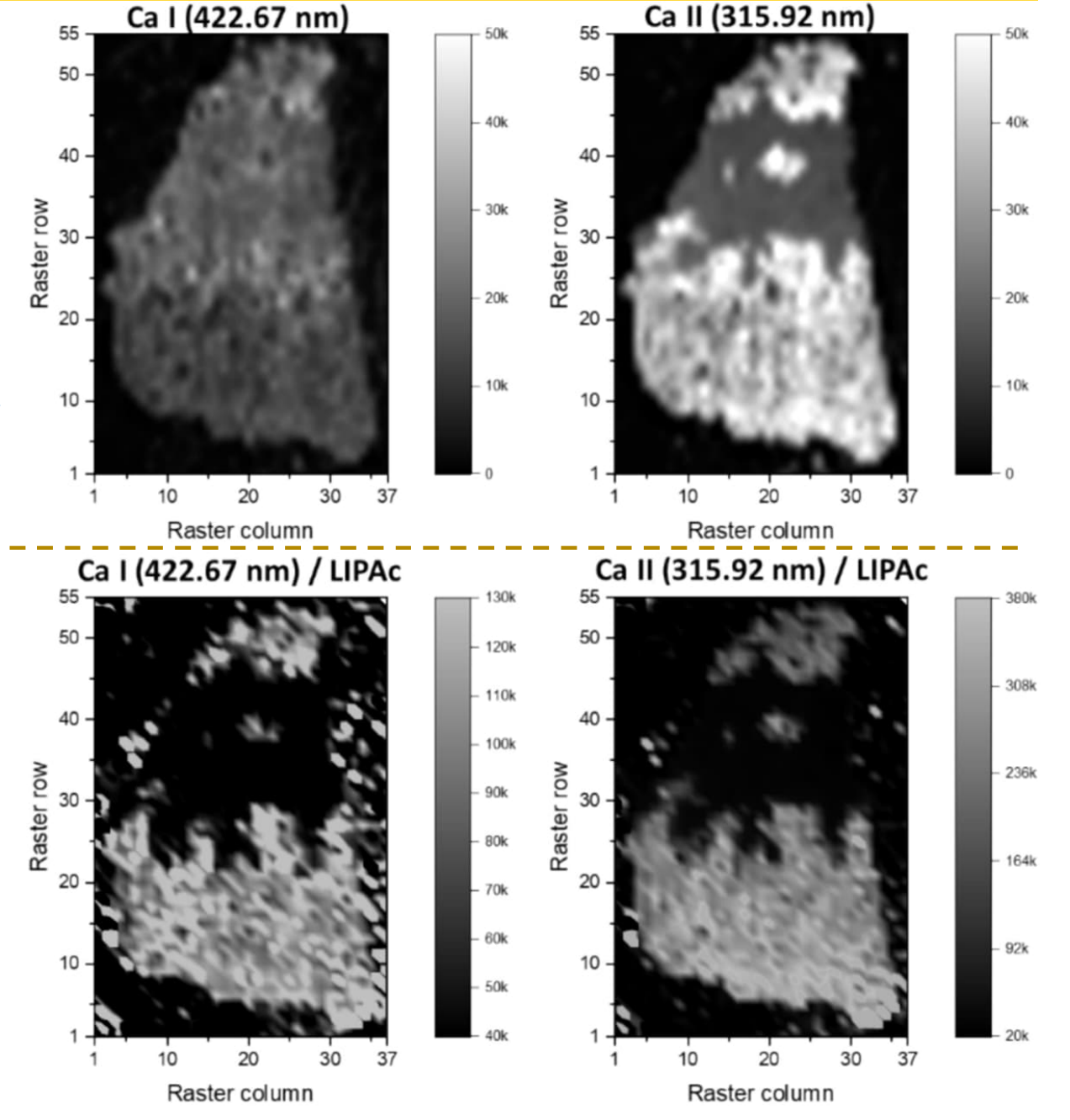


LIPAc map of the galena specimen



Chemical maps of the galena specimen created from raw LIBS intensities of atomic Ca at 422.67 nm (left) and ionic Ca at 315.92 nm (right).

LIPAc-normalized Ca chemical maps of the galena specimen.



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