

Electromagnetic Systems as a Valuable Complementary Tool for Anticipating Volcanic Unrest

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Abstract: This study evaluates whether abrupt geomagnetic changes systematically precede increases in local seismicity at the Chiles–Cerro Negro volcanic complex. Two unrest episodes, in October 2020 and July 2022, were analyzed using synchronized magnetometer records and seismic catalogs within ± 7 -day windows. Processing applied a 24-hour robust detrend, standardization, and a smoothed absolute-difference gradient; change-points were detected with CUSUM and PELT, and daily cross-correlations assessed lead–lag structure. Sub-daily energy was tracked with a 6–48-hour band proxy. In 2020, magnetic change-points preceded the main MLv 3.4 earthquake by approximately 58–60 hours; in 2022, they preceded the MLv 5.6 event by about 110 hours. Both episodes showed positive-lag correlation peaks, consistent with magnetometric variability leading seismic counts by days rather than minutes. Findings support low-cost, LoRa-enabled magnetometry as a complementary surveillance tool and motivate expansion the magnetometrics systems into volcanoes.

Keywords: Geomagnetic monitoring, Seismic precursors, LoRa communications, Cross-correlation, Change-point detection, Chiles-Cerro Negro.

1. Introduction

Electromagnetic observations complement seismic, geodetic, and geochemical monitoring by constraining pressurization and fluid migration within volcanoes. Their operational value in the Andes remains under-documented, motivating focused evaluations with clear performance criteria [1]. This study extends preliminary 2020 findings and a 2025 conference paper through a comparative analysis of two unrest episodes. It targets replicated lead times between abrupt magnetic changes and seismic bursts at the Chiles–Cerro Negro complex.

Recent volcanomagnetic studies demonstrate actionable signals with near-real-time interpretability, enabling alerting frameworks beyond research demonstrations. This emerging evidence motivates operational testing in Andean settings where documented use remains limited [2]. Comparative

time-series approaches estimate characteristic advances using overlap analysis and correlation, typically within windows of days [3].

Low-cost IoT architectures, including LoRa links, support continuous magnetometry with multi-kilometer telemetry under harsh conditions and modest power budgets. Recent stratovolcano deployments show reliable throughput and practical range, sustaining unattended stations [4]. In Ecuador, a 2020 prototype at “Chiles2” suggested magneto-seismic coupling, and a 2022 upgrade improved autonomy and communications.

The 2020 prototype comprised two scalar Overhauser stations: Chiles2, approximately three kilometers from the cone, and Thermal, six kilometers from Chiles2. Both used LoRa links to a receiver near Tulcán; power issues curtailed Thermal after several days, though key intervals were recovered [5]. The 2022 system retained Chiles2 with higher-capacity

solar, improved grounding and shielding, and refined LoRa settings. This analysis uses Chiles2 magnetometry and the local seismic catalog from 20 July to 1 August 2022 [6].

The objective is to test whether abrupt geomagnetic change-points precede increases in seismic activity during 2020 and 2022. The study examines replicability across episodes and quantifies lead-lag structure under consistent processing. Quality control retained samples above instrument thresholds, corrected recoverable format issues, resampled timelines, and synchronized magnetometry with seismic catalogs. A robust 24-hour detrend removed diurnal components, followed by z-score normalization [7].

Abrupt variations were computed as absolute first differences and smoothed using a two-hour median window to suppress noise while preserving steps. Change points were identified with CUSUM and PELT to capture the onset and structure of sustained regime shifts. CUSUM accumulates deviations to reveal persistent changes; PELT partitions the series by minimizing a penalized within-segment error. SSE denotes the sum of squared residuals within each segment and serves as PELT's optimization target. Lead-lag structure between daily magnetic variability and seismicity was assessed with Pearson cross-correlation and superposed epoch analysis.

Significance relied on non-parametric bootstrap and permutation tests, with external forcing screened and sensitivity analyses varying filters, aggregation, and window lengths. [7].

The structure of the article is as follows: Section 2 describes data processing, change-point detection, and significance testing. Section 3 presents episode-wise results, Section 4 provides a comparative discussion and operational implications and Section 5 concludes.

2. Methodology

In 2020, before the main event, the magnetic field oscillated within ~ 28660 – 28740 nT, displaying stable diurnal cycles. An abrupt change in the magnetic gradient began near 24 October at 00:00 UTC and persisted for multiple cycles. A MLv 3.4 earthquake occurred on 26 October 10:58 UTC shown in Fig. 1. The leading interval between the change-point and the main event is approximately 58–60 hours. A comparison was made of magnetometric variations and seismic activity around the two main events. The entries come from CSV files with UTC timestamps, synchronized and sorted chronologically.

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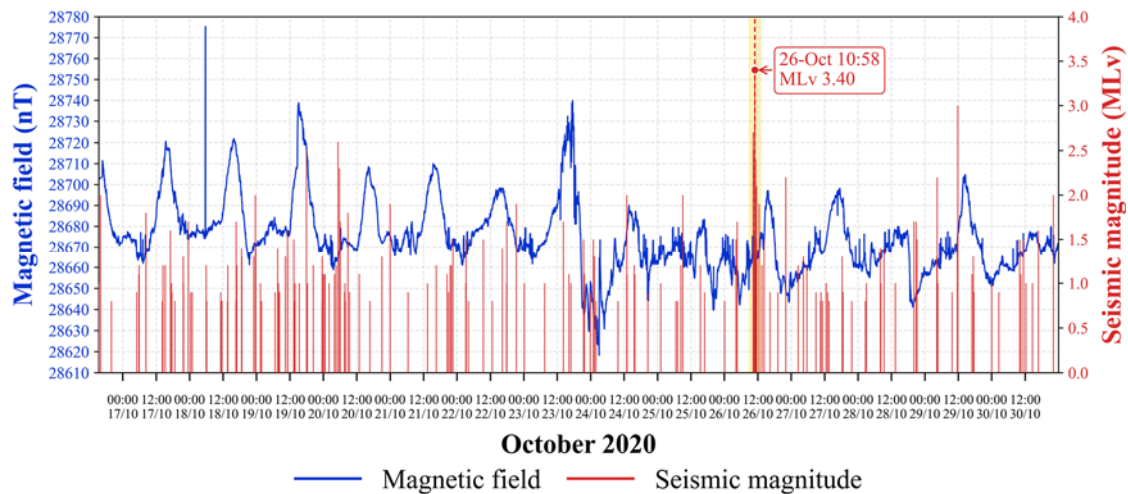


Fig. 1. October 2020. Magnetic field (left axis) and local seismic magnitudes (right axis) signal without processing. The shaded band marks the magnetic change-point preceding the MLv 3.4 event on 26 October 10:58 UTC.

Prior to the main event, the magnetic field ranged ~ 28500 – 28590 nT with stable diurnal behavior in 2022. An abrupt increase in the magnetic gradient began on 20 July 23:00 UTC and persisted over several days. A MLv 5.6 earthquake occurred on 25 July 13:33 UTC shown in Fig. 2. The leading interval between the magnetic change-point and the event is approximately 110 hours.

The analysis cuts symmetrical windows of ± 7 days for each event. All numerical columns are validated and non-convertible or missing values are removed

before processing. This subtraction attenuates slow regional effects and instrumental drift in the raw magnetic field. A 24-hour high-pass filter was applied, which is obtained by subtracting the 24-hour moving median. The result preserves subdiurnal fluctuations and reduces diurnal cycles and very low-frequency components, shown in Fig. 3.

For visual support, the 6–48-hour band is calculated as the difference between LP6h and LP48h. This trace highlights hourly and semi-diurnal patterns around the time of the event. Shown in Fig. 4.

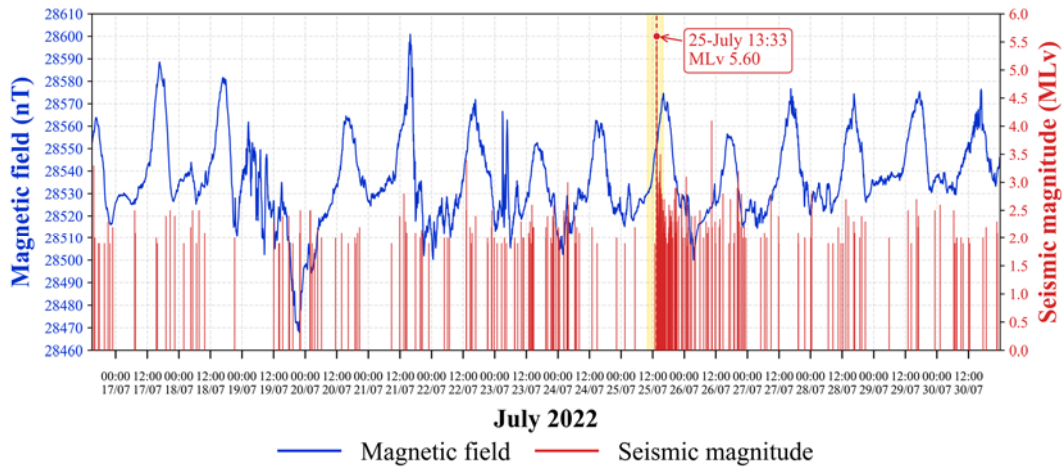


Fig. 2. Magnetic field (left axis) and local seismic magnitudes (right axis) at Chiles2 signal without processing. The shaded band marks the magnetic change-point preceding the MLv 5.6 event on 25 July 13:33 UTC.

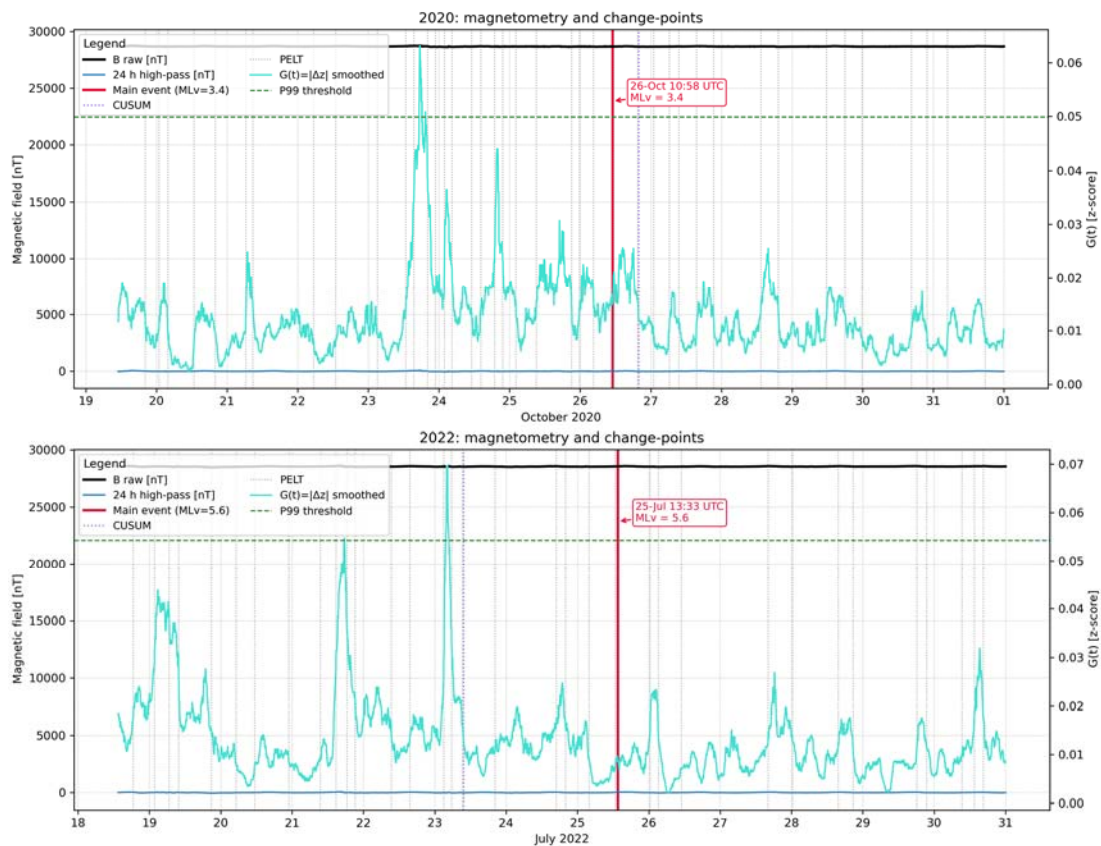


Fig. 3. Delimitation of the time window around the event in 2020 and 2022. The turquoise line represents $G(t) = |\Delta z|$ smoothed; the dashed green line shows the P99 threshold. The “24-hour high-pass [nT]” line shows the subtraction of the daily moving median from crude B.

Standardization uses the first five days of the window as a basis. $z(t)$ is calculated, and then $G(t)$ as the moving median of $|\Delta z|$ with two-hour smoothing. The P99 threshold corresponds to the 99th percentile of $G(t)$ within the basis. “Persistence” identifies the first 24-hour period with at least 95 % of samples above. The CUSUM detector, i.e., the cumulative sum of deviations, estimates a single global change using centered accumulations. PELT (optimal segmentation

algorithm) identifies multiple breaks by minimizing SSE (internal error of each segment) with β penalty and minimum segments close to two hours. Daily seismicity is obtained by counting events with magnitude $M \geq 1.5$. Gd is defined as the daily median of $G(t) = |\Delta z|$ smoothed, expressed in z-score and without units, calculated per calendar day. Nd is defined as the daily count of earthquakes with magnitude M greater than or equal to M_0 , using

$M0 = 1.5$ in this study. This aggregation homogenizes the temporal resolution and allows Gd and Nd to be compared by cross-correlation with

± 7 - day lags. Pearson's cross-correlation evaluates lags between -7 and $+7$ days, with permutation testing ($n = 2000$) for significance shown in Fig. 5.

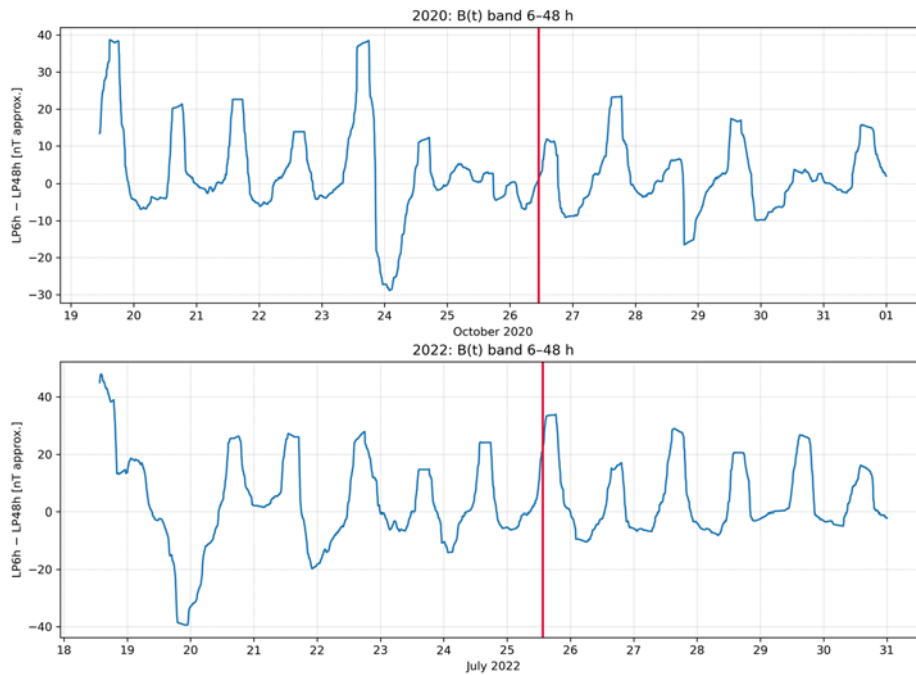


Fig. 4. LP6h-LP48h window for both 2020 and 2022. They highlight sub-components and time patterns close to the moment of the events.

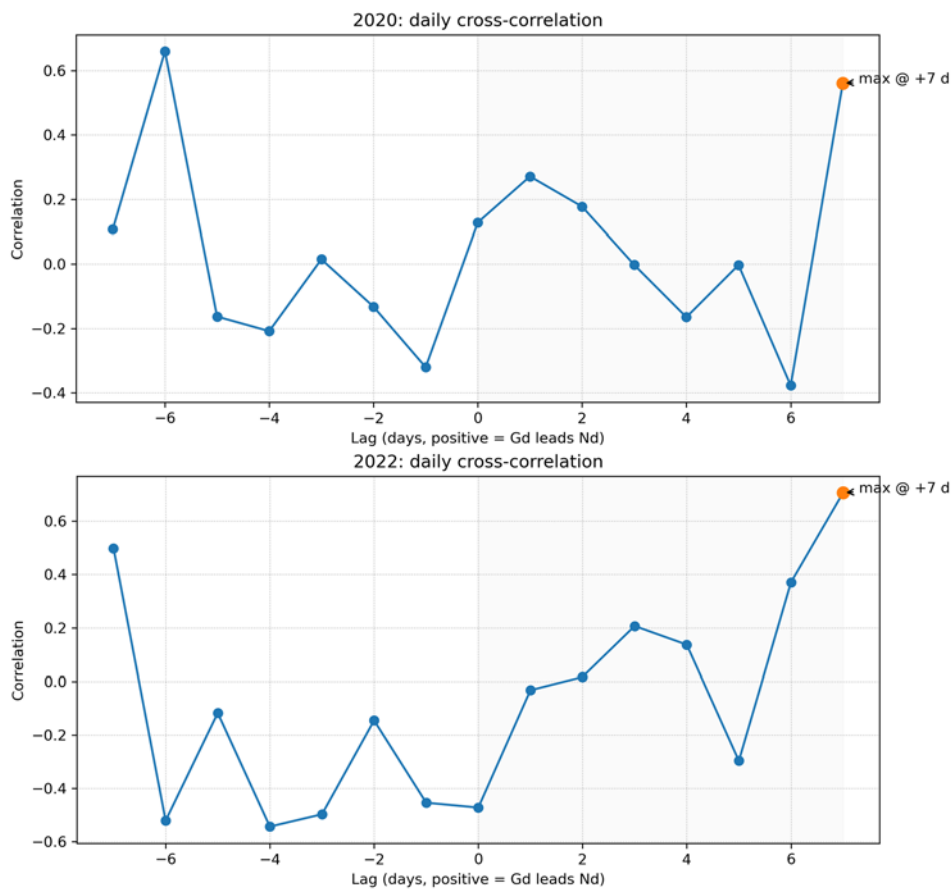


Fig. 5. Plot $\rho(\text{lag})$ for lags of ± 7 days and indicate the positive maximum and its displacement in 2020 and 2022.

Table 1. Magnetic Change-points vs. Main Seismic Events.

Episode	Change point (UTC)	Main Seismic Event (UTC)	Magnitude Seismic (MLv)	Lead Time (hours)
Oct 2020	24 Oct 00:00	26 Oct 10:58	3.4	58-60
Jul 2022	20 Jul 23:00	25 Jul 13:33	5.6	110

The analysis for October 2020 shows a subsidiary increase in the magnetic field after the 24th. The 24-hour high-pass trace shows increasing amplitude and greater variability prior to the $MLv = 3.4$ event. The $G(t)$ gradient exceeds the $P99$ threshold in a sustained manner approximately one day before the event. The $P99$ persistence window is clearly delimited until the main instant. The CUSUM detector identifies a dominant change point prior to the event. PELT segments several additional breaks that mark steps in pre-event variability. The daily cross-correlation between Gd and Nd shows maxima for short positive lags. These maxima suggest that magnetometric anomalies precede seismic counts.

For July 2022, a similar pattern is observed with a more pronounced subdiurnal amplitude. The 24-hour high pass increases its energy before the $MLv = 5.6$ event. $G(t)$ persistently exceeds $P99$ with an advance of about 24 hours. The $P99$ persistence band again precedes the time of the main event. CUSUM detects a global change consistent with the onset of intensification. PELT reveals multiple breaks that structure the preparatory phase into consecutive segments. Cross-correlation peaks with short positive lags.

This result supports that Gd leads Nd in the analyzed time scale.

4. Discussion

The two episodes exhibit reproducible magnetic precursors that lead seismic rate increases by days, not minutes. Lead times near 2.5 and 4.6 days were obtained. Agreement across $P99$ persistence, CUSUM, PELT, and daily cross-correlation strengthens the interpretation. A plausible mechanism involves progressive pressurization and fluid redistribution that modify conductivity and magnetic properties. Electrokinetic currents, piezomagnetism, and thermo-magnetic effects could jointly amplify sub-daily variability. The larger 2022 magnitude aligns with an earlier and stronger magnetic response.

Robustness arises from robust detrending, daily aggregation, and consistent change-point agreement. The 6–48 h band increase supports enhanced sub-daily energy before each event. Permutation tests on cross-correlations indicate that observed positive-lag peaks are unlikely by chance.

Important limitations remain: a single primary station, site effects, and possible catalog incompleteness near $M0 = 1.5$. But operationally, a

simple rule emerges: sustained $P99$ exceedance for at least 24 hours warrants an advisory watch. Combining CUSUM and PELT limits false positives and timestamps regime transitions. Cross-correlation of Gd against Nd provides an intuitive summary of lead-lag structure. Generalization is limited by two case studies within the same complex. More extensive testing is required on Andean volcanoes in Ecuador. Future work should implement real-time processes with adaptive thresholds and environmental covariates.

5. Conclusions

Two independent unrest episodes at Chiles–Cerro Negro show magnetic change-points leading significant seismic events by several days. Results support integrating low-cost magnetometry into multiparameter surveillance and calibrating operational thresholds.

This study identified reproducible magnetic precursors that led seismic rate increases by days in 2020 and 2022 at Chiles–Cerro Negro. Lead times near 2.5 and 4.6 days were estimated with consistent indicators. Concordant detections from $P99$ persistence, CUSUM, PELT, and daily cross-correlation support a genuine pre-seismic magnetic signal. The 6–48-hour band increase corroborated enhanced sub-daily variability preceding each main event.

It is recommended to maintain and expand the magnetometry network as part of routine Instituto Geofísico monitoring, prioritizing multisite arrangements and common references to suppress common mode.

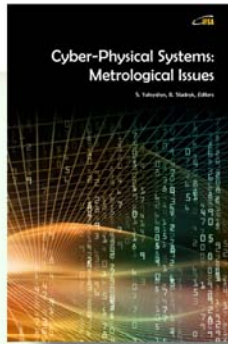
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