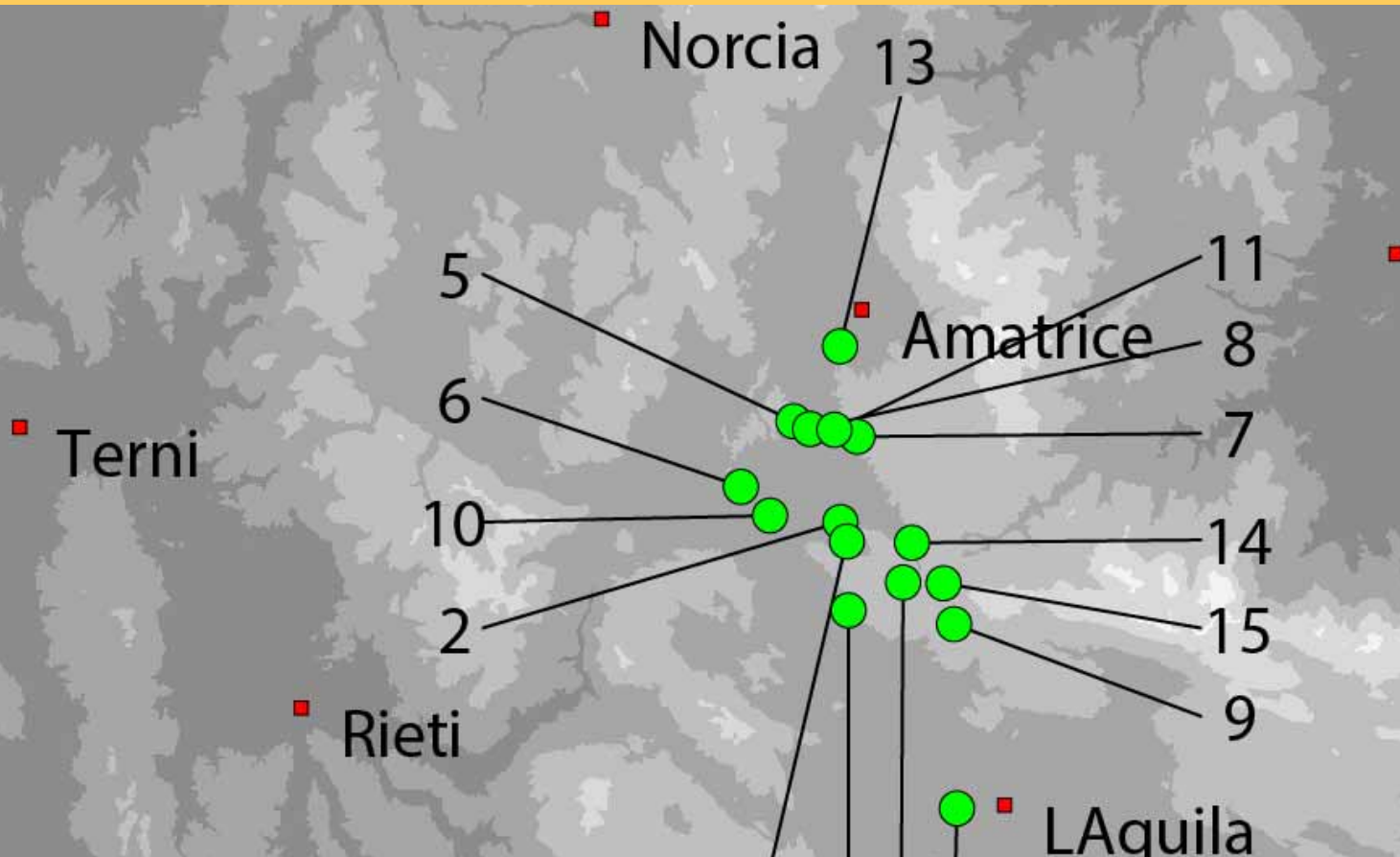




RAPPORTI TECNICI INGV

Evaluation of the Impact of Potentially
Compromised Stations on the
Localization of Seismic Events



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Evaluation of the Impact of Potentially Compromised Stations on the Localization of Seismic Events

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Cover map of the studied area (Central Appennines) with the earthquakes selected for this study | *In copertina Mappa dell'area di interesse (Appennino Centrale) con i terremoti selezionati per questo studio*

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Abstract

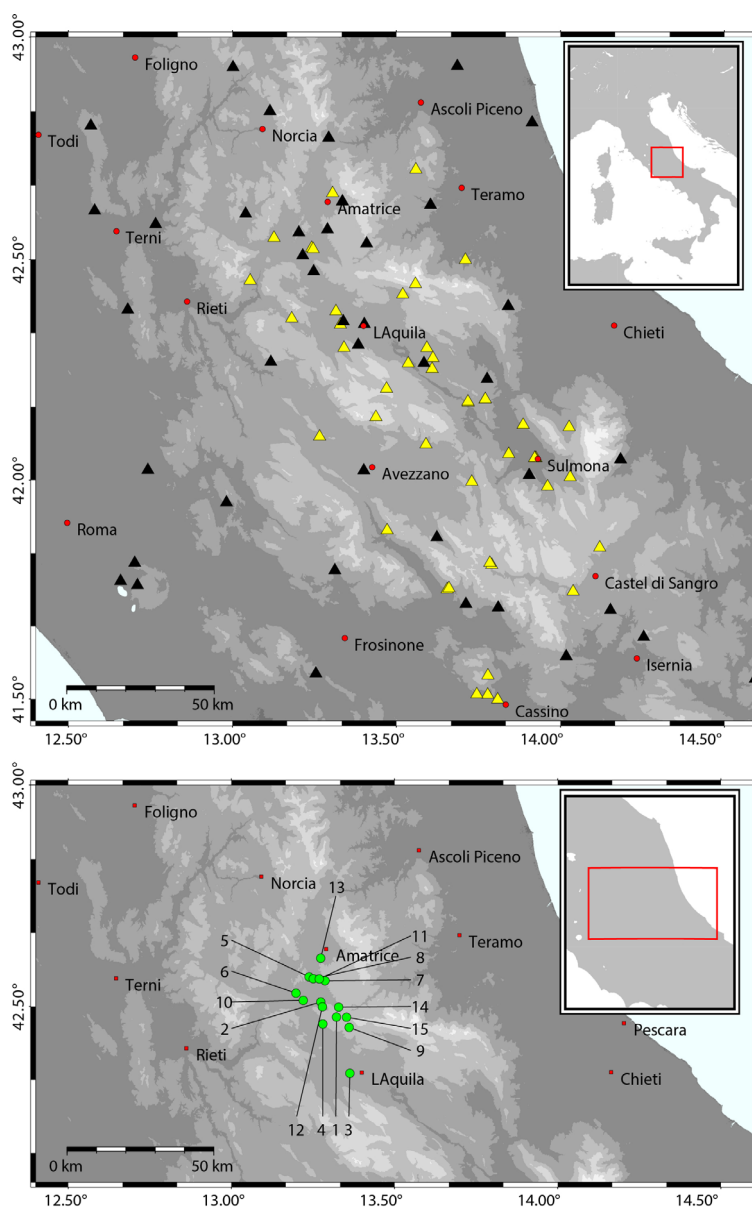
This study analyzes data from a Local Seismic Network affected by documented random time synchronization errors, aiming to develop correction strategies to improve earthquake location accuracy, particularly for moderate to small events. The work focuses on optimizing data usage in hypocentral locations and focal mechanisms in a seismically active area where the Italian National Seismic Network (RSN) has uneven station coverage. With this aim, 15 seismic events recorded by the local Rete Sismica Abruzzo (RSA) and RSN between 2007 and 2016 in the central Apennines were selected. First, we assess the effectiveness of the automatic picking procedure by re-picking the first arrivals of P- and S-waves in RSN data that we previously picked manually. Then, we applied the automatic picking procedure to RSA data using the SeisBench toolbox and PhaseNet model to reduce potential analyst-related errors. Both datasets are then processed with Hypoellipse for event relocation and FOCMEC for focal mechanism inversion. Five inversion tests were performed to assess the influence of RSA on final solutions in terms of error, varying the codes assigned to P- and S-phase arrivals. We explore ts - tp differential times (where ts and tp denote the arrival times of the S and P phases) as a correction strategy to integrate RSA data into hypocentral solutions. Results indicate that the sole integration of RSA data improves earthquake detection quality regarding azimuthal gap, minimum epicentral distance, horizontal and vertical errors, and RMS values, except for some events. Moreover, using ts - tp arrival differences helps mitigate clock synchronization errors, enhancing the event's location and focal mechanism accuracy. However, assigning lower weights to RSA data can sometimes reduce the reliability of the estimates. The findings suggest that careful weighting of these differences is essential to ensure high-quality seismic analyses even when using ts - tp intervals as a corrective measure.

Keywords Seismic Local Network; Automatic picking; Focal mechanisms

Introduction

Seismic monitoring of the Italian territory is one of the primary activities of the National Institute of Geophysics and Vulcanology (INGV). This scope is achieved with the Italian National Seismic Network (RSN), a permanent network which is distributed throughout the entire territory [Istituto Nazionale di Geofisica e Vulcanologia, 2005], and in collaboration with Local Seismic Networks and observatories [Cattaneo and Moretti, 2011]. While INGV manages the RSN, other seismic networks also contribute to collecting seismic signals. Nowadays, this network consists of more than 500 permanent seismic stations, equipped with a variety of instruments and its configuration has changed over the years. The RSN primarily consists of three-component broadband velocimeters or three-component strong-motion accelerometers paired with a GPS system and a telemetry system. Its spatial distribution is uneven and denser in areas where significant seismic events have occurred (Figure 1).

Figure 1 Maps of the studied area. Top, yellow triangles represent the RSA stations while the black ones are the RSN stations. Note that not all of the listed RSA and RSN stations were operational throughout the entire selected time window. Bottom, green dots represent the selected events with their relative Eq number (see also Table 1).



The Abruzzo Regional Seismic Network (RSA) played a fundamental role in the central Apennines, especially during the Mw 6.3, 2009 L'Aquila earthquake [Chiarabba et al., 2009]. This network was installed at the end of 1991 throughout the Lazio-Abruzzo region and has been active for about 30 years. It comprises 18 seismic stations connected with short-period sensors, Mark L4C-3D [De Luca, 2011]. Since 2005, all the instruments have been equipped with Lennartz Mars88-Modem Control, which employs GSM modems for collecting data [De Luca, 2011]. These stations were configured with a "triggered-based" recording system, whereby data acquisition was not continuous but is activated when at least three stations were triggered by seismic activity within a 1-minute time window, corresponding to the sum of the pre and post event. At each station, the triggered condition was defined as:

$$R = \frac{STA}{LTA + level}$$

Where STA = 1s, LTA 100s and *level* is between 20-100 counts. *R* ranged between 1.8 and 3.5, depending on the seismic noise level at each station, and this threshold had to be met on at least 2 out of 3 channels. Time synchronization signal was achieved using a DCF radio signal transmitted by a European station in Frankfurt, Germany [D'Alema et al., 2005] and GPS antennas.

Nevertheless, this timing method presents limitations, as solar irradiation can interfere with the signal; to address these issues, all RSA stations have been equipped with an external GPS antenna, which provides precise timing through a GPS receiver, which regulates the station clocks. While the instrumental enhancement has mitigated the timing issue associated with the radio signal, a further problem concerns the loss of synchronization with the GPS clock for some RSA stations. All the stations that experienced this issue were documented in a personal repository. All of the aspects described highlight that the integrated use of these data for seismological analysis is challenging. In this technical report, we describe the analysis we carried out to identify and suggest the most effective approach for uniformly integrating the RSA data with recordings from the RSN and show how they can better constrain earthquake source parameters.

1. Data Selection

Our analysis aims to develop a correction strategy to integrate RSA data with RSN ones into seismic studies, even when the recordings are affected by random time synchronization errors. We selected a dataset of seismic events within an area well covered by the RSN and the RSA networks, extending from the middle Aterno Valley to the municipalities of Amatrice and Norcia. In detail, we focused on seismic events recorded between January 1, 2007, and August 23, 2016, including earthquakes with magnitude $M_I \geq 2.5$. The chosen period aligns with the instrumental upgrade involving the Lennartz Mars88-Modem Control and the external GPS, as well as the Mw 6.1, 2016 Amatrice earthquake, when the RSN underwent a partial increase in the number of stations in response to the seismic sequence. However, we excluded from the selection all the events occurring after the L'Aquila earthquake, as all the RSA stations were subject to continuous monitoring due to the ongoing seismic sequence.

Subsequently, the selection was refined by cross-checking with stations documented to have experienced such technical issues. In detail, these data were listed as "*station name, starting date of the issue, GPS state, ending date of the issue*". When one or more of these indications were missing, the period for event investigation was defined as:

- When the GPS state was "ON," we investigated events occurring during the week preceding the reported date.
- When the GPS state was "OFF," we investigated events occurring during the week following the reported date.
- When the GPS state was not specified, we investigated events occurring within two weeks, including the week before and the week after the reported date.

This cross-check confirmed that no crashes were reported in 2007 and 2010. According to the above criteria, we discovered 39 earthquakes from 2011 to 2016 that may have been recorded by at least one compromised RSA station. Due to the paucity of compromised stations identified for the selected events, we chose 15 earthquakes that meet the initial criteria, including those with and without compromised seismic stations. Here is the final list (Table 1).

Eq	#CODE_ID	Data	UTC Time	Magnitude	MagType
1	1722489	2007-02-17	19:35:40	2.5	MI
2	1832219	2008-07-09	09:47:21	3.1	MI
3	1877139	2009-01-16	22:47:24	2.5	MI
4	2271049	2010-10-17	08:43:27	2.9	MI
5	2368109	2011-06-02	07:42:00	2.6	MI

6	2477379	2012-01-18	15:59:19	2.7	MI
7	998101	2012-06-22	00:36:11	2.8	MI
8	1087701	2012-07-16	14:25:53	2.6	MI
9	1696381	2013-01-25	04:27:51	2.9	MI
10	2355161	2013-07-18	12:21:54	2.6	MI
11	4019501	2014-08-04	06:04:42	2.9	MI
12	5324791	2015-04-23	16:55:42	2.6	MI
13	5967911	2015-08-18	13:59:11	2.7	MI
14	6382251	2016-01-18	10:37:17	3.3	MI
15	6415111	2016-02-01	09:11:48	2.9	MI

Table 1 List of the selected events. #Code_ID refers to the event identifier assigned by INGV (see Figure 1).

2. Preprocessing

Before the event localization, we needed to preprocess the RSA waveform data. We manually picked and reviewed the RSN waveforms using SeisGram2K software [Lomax A., 2014], whereas, for the RSA data, we used an automatic picking procedure to reduce the analyst errors to the first arrival time estimation. The automatic identification of the P and S phases was performed using the SeisBench toolbox [Woollam et al., 2022] with the Phasenet model [Zhu & Beroza, 2018], while the first-motion polarities of the P-wave arrivals were determined using an adapted version of the First Motion Polarity Classification (FMPC) model by Ross et al. [2018]. The efficiency of the automatic procedure was evaluated by re-picking the RSN data for all 15 events. Specifically, the effectiveness was assessed by comparing the percentage ratio of automatically detected P- and S-phases and polarities to those identified manually (see sections 2.1 and 2.2).

2.1. Manual VS Automatic P- and S-phases picking

A direct comparison between manually and automatically picked phases was conducted to further investigate the reliability of the automatic procedure before applying it to the RSA data. For this reason, we applied our comparison to the RSN data. In detail, a comparison was performed to assess how many phases were detected, their consistency across events, and the overall effectiveness (computed as the percentage ratio of automatically detected phases, P or S, to those manually identified) of the approach (Table 2). We automatically picked the seismic recordings for each event using the SeisBench toolbox with the Phasenet model, which had already been tested for detecting first arrivals in the Italian territory [Woollam et al., 2022; Münchmeyer et al., 2022], demonstrating high performance and reliability. When using PhaseNet, setting a probability threshold is crucial for filtering the detected arrivals. Specifically, a threshold value refers to the coincidence level required for a detection to be considered a true positive [Zhu & Beroza, 2018]. This value can be tuned to improve the performance of the prediction, but it does not affect the arrival time of the phase [Zhu & Beroza, 2018]. For our analysis, a probability threshold of 0.3 was set for both P- and S-wave picks to include uncertain arrivals, which generally correspond to one or two P or S phases per event. This decision was made considering the available RSN stations in 2007-2009, and the high noise level affecting seismic recordings at stations far from the epicentral area.

The comparison in Table 2 shows that for 12 of the 15 selected earthquakes, the automatic picking technique successfully detected the P-wave first arrival in more than 85% of the recording stations, with 3 of these events achieving a 100% detection rate (see Table 2 columns “Effectiveness”, subcolumn “P-pha”). Three events show lower detection ratios (EQ1, EQ6, and EQ 10 in Table 2). For each of these earthquakes, the P-wave first arrivals could not be derived at more than three stations, likely due to their small magnitude (see Table 1) and the presence of noise in waveforms, which prevented the signal from exceeding the imposed probability threshold required for detection. According to our experience, the detection rate can be improved by lowering the probability threshold value; however, a manual review would then be necessary to prevent the inclusion of false positives.

S-wave first arrivals have higher amplitude, allowing for a greater detection rate than P-wave first arrivals when using the automatic procedure. Hence, for some stations, only the S-wave first arrival passes the 0.3 probability threshold; thus, this information alone could not be used in the following steps of the procedure.

For many events, automatic picking allows the identification of both the P- and S-wave first arrival compared to the manual pick (in Table 2, see “S/P Detection Ratios”). Indeed, the automatic picking procedure successfully identified both phases in more than 85% for 13 events and achieved 100% for 4 (see column “Automatic” in Table 2 for details).

As a result, unlike manual picking, the automatic procedure achieves a higher detection rate of the S-wave first arrivals, doubling, in some cases, the S phases manually identified (EQ14, columns “S-pha” in “Manual picking” and “Automatic picking” in Table 2). This increases the percentage ratio of automatically detected S-phases surpassing the 100%. Concerning the detection of the P-wave first arrivals, the effectiveness ratio is in the 73% of the selected cases higher than 85%.

Eq	Manual picking		Automatic picking		S/P Detection Ratios		Effectiveness	
	P-pha	S-pha	P-pha	S-pha	Manual	Automatic	P-pha	S-pha
EQ1	13	9	9	8	69%	89%	69%	89%
EQ2	13	11	13	11	85%	85%	100%	100%
EQ3	13	7	10	9	54%	90%	77%	129%
EQ4	25	21	24	23	84%	96%	96%	110%
EQ5	15	9	13	12	60%	92%	87%	133%
EQ6	12	6	9	5	50%	56%	75%	83%
EQ7	14	10	12	12	71%	100%	86%	120%
EQ8	11	10	11	10	91%	91%	100%	100%
EQ9	16	12	15	14	75%	93%	94%	117%
EQ10	17	10	12	5	59%	42%	71%	50%
EQ11	21	11	18	17	52%	94%	86%	155%
EQ12	15	8	14	14	53%	100%	93%	175%
EQ13	18	9	17	16	50%	94%	94%	178%
EQ14	15	7	15	15	47%	100%	100%	214%
EQ15	17	9	16	16	53%	100%	94%	178%

Table 2 Comparison of Manual and Automatic Picking of P- and S-wave first arrival. Eq = event id (refer to Table 1 for the list), P-pha = Number of the detected P phases, S-pha = number of the detected S phases. S/P Detection ratios = percentage ratio of detected S phase to P phase for each event. Effectiveness = Percentage ratio of automatically detected phases (P or S) to those manually identified.

The delta time, Δt , is calculated as the difference between the manual and automatic detected pick. A positive value indicates that the automatic phase pick occurs earlier than the manual one, while a negative value means the opposite. The minimal time differences in the picked arrival times further support the agreement between the two approaches. As shown in Table 3, these differences are mostly minimal, in the order of 0.01 of a seconds.

Eq	P-pha			S-pha			P-pha		S-pha	
	$\Delta t_{\min}$	Δt_{avg}	$\Delta t_{\max}$	$\Delta t_{\min}$	Δt_{avg}	$\Delta t_{\max}$	$\Delta t \geq 0$	$\Delta t < 0$	$\Delta t \geq 0$	$\Delta t < 0$
EQ1	0.03	0.06	0.19	-0.14	0.03	0.12	9	0	6	1
EQ2	-0.08	0.02	0.09	-1.05	-0.12	0.06	12	1	5	5
EQ3	-0.03	0.04	0.09	-0.37	-0.04	0.11	9	1	3	2
EQ4	-0.05	0.06	0.33	-0.06	0.23	1.68	23	1	18	2
EQ5	0.01	0.03	0.06	0.02	0.05	0.13	13	0	8	0
EQ6	0.01	0.04	0.09	-0.16	0.00	0.07	9	0	4	1
EQ7	0.02	0.05	0.16	-0.11	0.03	0.21	12	0	6	3
EQ8	-0.01	0.02	0.05	-0.01	0.05	0.13	9	2	8	1
EQ9	-0.08	0.02	0.14	0.01	0.08	0.26	12	3	11	0
EQ10	-0.03	0.05	0.21	-0.08	0.05	0.24	10	2	1	2
EQ11	-0.01	0.04	0.08	-0.01	0.05	0.11	17	1	9	1
EQ12	0.01	0.04	0.09	0.01	0.09	0.44	14	0	8	0
EQ13	-0.10	0.03	0.24	-0.35	0.05	0.27	14	3	7	1
EQ14	0.00	0.03	0.08	-0.04	0.09	0.33	15	0	6	1
EQ15	-0.04	0.02	0.06	0.03	0.14	0.56	14	2	9	0

Table 3 Minimum (min), Average (avg) and Maximum (max) time differences in seconds (Δt) for the P- (P-pha) and S-phases (S-pha), computed the difference between the manually and automatically picked arrival times at each station. Number of positive ($\Delta t \geq 0$) and negative ($\Delta t < 0$) differences in time for both P- and S-phases.

It is also important to note that, although the Δt is minimal, the automatic procedure generally detects the first arrivals of the seismic phases earlier than the analyst (see the last four columns in Table 3). Nevertheless, the two approaches yield comparable results and thus demonstrate the reliability of the automatic picking process, regardless of the magnitude of the analyzed events.

2.2 Manual VS Automatic polarities detection

To further evaluate the reliability of the automatic procedure, a comparison between manually and automatically identified P-wave polarities was performed. The first-motion polarities detection was performed using a *supervised automatic procedure that employs the FMPC model* [Ross et al., 2018]. We implement a sliding window application of the FMPC model that improves the robustness of the polarity detection to arrival time picking errors. Precisely, the FMPC model was designed to classify the polarity of a detected arrival occurring at the center of a 4-second waveform window, assigning a single label (Up/Down/Unknown) to the whole waveform segment [Ross et al., 2018]. This approach is sensitive to the accuracy of the phase arrival time determination, as it must lie exactly at the center of the waveform window for an accurate prediction. On the contrary, our approach applies the model using a sliding window centered around each time sample ± 0.5 sec around the first arrival pick time, from which we then use the mean value for each predicted class ("mean label") to determine the probable polarity class.

The selected approach enhances polarity detection by providing distinct estimations for the model that most accurately solves the P-wave first-motion arrival. Consequently, it provides at least two single-window and sliding-window labels, respectively. If neither approach solves the polarity, the second most probable class from the sliding-window approach is returned. We made this choice to maximize the number of detectable polarities.

We applied the algorithm to all the RSN recordings previously re-picked automatically. Specifically, the polarities are determined without performing a new picking with the P-wave picking model from Ross et al., 2018; instead, we directly impose the arrival times estimated by Phasenet (see section 2.1). Then, the code identifies a 4-second time window around the P-wave first-arrival and labels the signal within that interval. Nevertheless, the procedure for the polarity identification is *supervised* by the analyst, who makes the final decision on determining the model that best aligns with the first-motion arrival or adding a label for the uncertain polarities.

As a result, utilizing the sliding-window approach and averaging the labels assigned at each point along the subsequent probability trace proved to be the most effective approach for enhancing the detection of first-motion polarities. It is important to note that for all the selected events, the first most probable class predicted this way (see "Mean" in Table 4) does not determine the first-motion polarity, consistently assessing the label "Unknown". This outcome could be a consequence of the 0.3 probability threshold applied during the picking step, which allows the detection of P-wave first arrivals that may not be well-defined. Consequently, averaging a sequence of alternating "Up" and "Down" labels likely yield an uncertain polarity classification. Nevertheless, the predictions of the second most probable class exhibit a high agreement ratio, accurately determining 100% of the polarities for all the events (see Table 4, "sliding window", column "Ratio").

Eq	N _{tot}	Single Window		Sliding Window			Nmatch	Effectiveness
		Ross	Ratio	Mean	2 nd class	Ratio		
EQ1	9	4	44%	0	9	100%	9	100%
EQ2	13	4	31%	0	13	100%	10	77%
EQ3	11	2	18%	0	11	100%	8	73%
EQ4	24	14	58%	0	24	100%	22	92%
EQ5	13	7	54%	0	13	100%	11	85%
EQ6	9	3	33%	0	9	100%	9	100%
EQ7	12	7	58%	0	12	100%	10	83%
EQ8	11	6	55%	0	11	100%	10	91%
EQ9	15	8	53%	0	15	100%	10	67%
EQ10	12	0	0%	0	12	100%	8	67%
EQ11	18	3	17%	0	18	100%	16	89%
EQ12	14	2	14%	0	14	100%	13	93%
EQ13	17	3	18%	0	17	100%	15	88%
EQ14	15	4	27%	0	15	100%	14	93%
EQ15	16	9	56%	0	16	100%	15	94%

Table 4 Comparison of Manual and Automatic identification of P-wave first arrival polarity. Eq = event id (refer to Table 1 for the list), N_{tot} = total number of P phases detected automatically for each event. Ross = total number of polarities identified (U or D) by the FMPC model (single-window approach), Mean = total number of first-class predicted polarities identified (U or D) by the sliding-window approach, 2nd class = total number of second-class predicted polarities identified (U or D) by the sliding-window approach. Ratio = Percentage ratio computed as the number of polarities identified divided by the total number of phases. Nmatch = total count of automatic polarities that align with the manually identified ones, Effectiveness = Percentage ratio of automatically detected polarities to those manually identified.

In conclusion, for 87% of the analyzed events, the automatically detected polarities match the manually identified ones in more than 70% of the stations, demonstrating the reliability of both the sliding window application of the FMPC model and the resulting estimations.

2.3 Integration of the RSA data

Given the reliability of the automatic procedure, it was then applied to detect the first arrivals for the RSA seismic recordings of all the selected events, following the approach described in sections 2.1 and 2.2.

A comparison between the RSN and RSA data, derived from manual and automatic picking, indicates that, despite the difference in the number of stations (hereafter N_{sta}), the total number of identified phases, P and S, (hereafter N_{tot}) remains comparable. In detail, a minimum of 11 RSN and 8 RSA recording stations were used for each selected event. The maximum RSN N_{sta} per event is 25, with the highest N_{tot} is 46. For RSA the maximum N_{sta} used for a single event is 18 while N_{tot} is 34. The automatic picking procedure detected a total of 363 P and S phases across all selected events, which is comparable to the 384 P- and S-phases identified through manual picking, considering the difference in the N_{sta} between the two networks. Overall, the automatic approach detected more S phases, totaling 177 for the RSA and 149 for the RSN, while providing more reliable error estimates. More information is listed in Table 5.

	RSN			RSA			RSN+RSA		
	N_{tot}	N_p	N_s	N_{tot}	N_p	N_s	N_{tot}	N_p	N_s
MIN	18	11	6	16	8	8	37	19	17
MAX	46	25	21	34	18	16	71	38	33
AVG	26	16	10	24	12	12	50	28	22
TOT	384	235	149	363	186	177	747	421	326

Table 5 Minimum (MIN), maximum (MAX), average (AVG) of N_{tot} phases detected across the selected events, and total (TOT) N_{tot} phases detected for all the events. N_{tot} = Total number of phases per event, N_s = Number of S-wave phases per event, N_p = Number of P-wave phases per event. Each column should be interpreted independently; the values in N_p and N_s do not necessarily sum to N_{tot} for the same network.

The consistency of the results is also evident in the detected polarities. Although not directly comparable, the U-GPD model identified 186 P-wave polarities, including 106 compressional (Up) and 76 dilatational (Down) phases. Among these, only 4 polarities are unknown (Table 6).

	TOT	U	D	N
RSN	235	174	59	2
RSA	186	106	76	4

Table 6 Total (TOT), Up (U), Down (D) and Unknown (N) number of P-wave first-motion polarities for the RSN and the RSA.

The integration with the RSA nearly doubles the total N_{tot} detected, significantly improving phase identification and estimation accuracy.

3. Locating Earthquake

Different inversion tests were performed to assess the impact of the compromised RSA stations on earthquake location. Considering the possibility that synchronization errors at some stations may not have been recorded, all the RSA absolute times are regarded as equally erroneous in these trials. In detail, the selected events were relocated using the Hypoellipse code [Lahr J.C., 1989], employing a region-specific velocity model [Giacomuzzi G., 2023] and applying five different inversion schemes. These schemes were designed to investigate how to integrate the RSA data with the RSN ones in locating earthquakes. The following runs were executed:

Test1: We used only the first arrivals detected at the RSN stations. A weight-code must be assigned to each phase to indicate its reliability in the hypocentral solution. This code represents a relative standard error in second and ranges from 0 to 4, with 0 indicating a clear first arrival and 4 indicating phases too uncertain to be used. In *Test1*, a weight-code of 0 was assigned to each identified P-phase, while the weights for each S-phase ranged from 1 to 3, depending on the analyst's ability to identify the arrivals. We use this test as a reference for the next trials.

Test2: We integrated the RSN and RSA data while maintaining a weight-code of 0 for all the P-wave first arrivals from both networks. A weight-code of 1 was assigned to all the RSA S-waves first arrivals identified through the automatic picking procedure; this weight-code corresponds to a standard error of 0.5 s as referenced in the Hypoellipse manual [Lahr J.C., 1989]; see tables A.1 in Appendix for details. This trial aims to evaluate the potential variation in event location resulting from the simple integration of the RSA stations. In this case, we assume that no RSA stations have been affected by GPS synchronization issues and that the absolute time of the data is correct. However, given that some stations are known to be affected by these issues, an increase in event residuals is expected, if compared with the previous trial. We use this test also as a baseline reference, as it represents the first practical implementation of RSA station integration.

Test3: We accounted for the possibility that some RSA stations may be compromised. As previously mentioned, it cannot be excluded that some technical issues were not documented for certain RSA stations. We decided to explore the most probable and worst-case scenario to assess the maximum potential impact of compromised stations so we assumed these issues could affect all RSA stations. A weight-code equal to 9 is assigned to all the RSA P-waves first arrivals. Hypoellipse enables the use of the *ts-tp interval*, which is the time difference between the S-wave first arrival (*ts*) and the P-wave first arrival (*tp*), in the hypocentral solution, while the weight-code is assigned to the S arrivals, indicating the weighting desired for the *ts-tp interval*. This approach can help to overcome possible challenges during the integration process by fixing the epicentral distance for the RSA stations. As an initial trial, this method is applied without assigning an error to the *ts-tp* time difference. In detail, a weight of 0 was applied, assuming the time difference to be accurate, with a standard error of 0.1 seconds or less. Since *Test3* constitutes an improvement of the previous trial, we expect to obtain more stable solutions. However, to take into the account alle the uncertainty from the picking process we set this test as the baseline for the last two runs.

Test4: We varied the *ts-tp* uncertainty, assigning a weight-code of 1 to all the *ts-tp intervals*. This choice implied a standard error between 0.1 and 0.5 s for the time difference. In this trial we consider the presence of possible errors in the *ts-tp* time difference. Given that it is unrealistic to assume that the *ts-tp interval* is not affected by uncertainty, we expect these solutions to be more reliable compared to the ones obtained with *Test3*.

Test5: We assigned a weight-code of 2 to all the *ts-tp* uncertainty. In this case, the standard error ranges from 0.5 to 1.0 s for these intervals. In this case, we increase the uncertainty associated with the *ts-tp interval*. As the errors in seconds are starting to get significant, we expect to obtain less constrained solutions. The last two tests (*Test4* and *Test5*) explored the impact of different weight assignments to the *ts-tp intervals* on the final earthquake locations.

Significant variations are observed between *Test1* and *Test2* (T1 and T2 in Figure 2), as data from RSN were integrated with RSA stations. Specifically, the results of the inversion tests demonstrate that the integration of RSA stations (test T2 in Figure 2) enhanced earthquake location parameters, primarily by reducing azimuthal gaps (GAP), horizontal errors (*SEH1* and *SEH2*), and vertical errors (*SEZ*) (see Figure 2). A slight improvement is also observed in the minimum distance between the epicenter and the closest station (*Dmin*), though this is inconsistent across all events. Results from *Test3*, *Test4*, and *Test5* exhibit stable azimuthal gap values (Figure 2), highlighting the adequate instrumental coverage ensured by the RSA stations. In contrast, variations are observed in the *Dmin*, *SEH1*, *SEH2*, and *SEZ* values. These variations are attributed to the methodology employed for integrating RSA data, which relies on the *ts-tp interval*. Using this option during the location process applies constraints to the hypocentral distance. As a result, adjusting the weight assigned to this time difference can affect the estimated parameters. A systematic increase in these values is observed for horizontal and vertical errors as the weight assigned to the RSA data increases (T3, T4 and T5 in Figure 2). This point highlights that increasing the weight assigned to the *ts-tp interval* allows for greater flexibility in the results, as it accounts for possible uncertainties in picking seismic phases and provides reliable solutions. Further evaluation indicates that the station distribution quality, *D* or *QD* as defined in HYPO71 [Lee and Lahr, 1972] (see Appendix A.2), is classified as A for 67% of events in *Test1* and for 93% of events across all other tests, confirming adequate instrumental coverage.

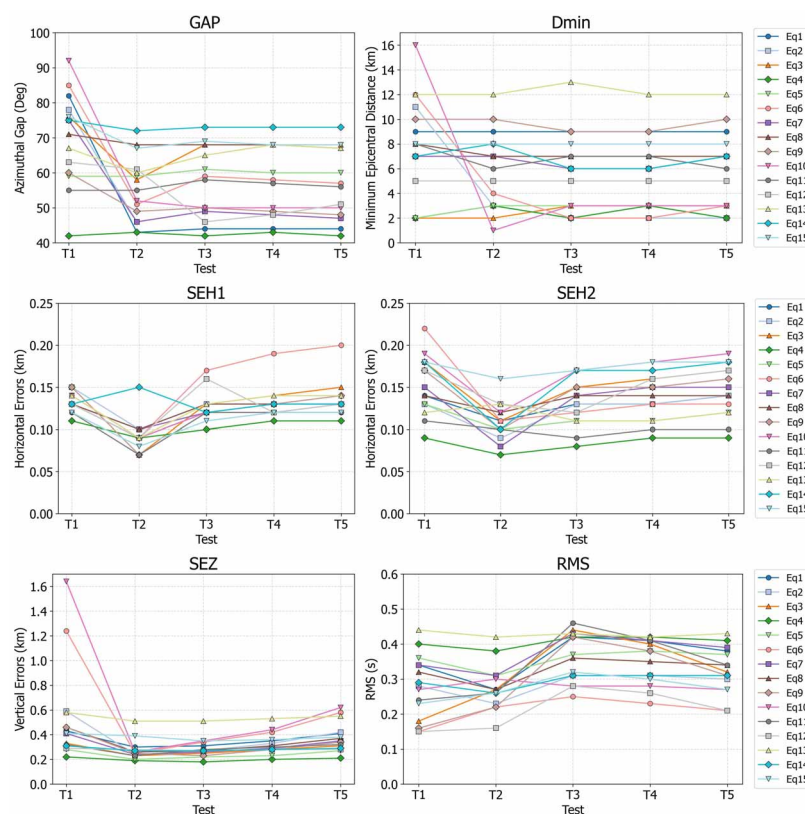


Figure 2 Earthquake localization parameters computed for all relocation trials (*Tests*), with corresponding markers and colors indicated in the associated legend.

The RMS error values show a more chaotic behavior (Figure 2) if compared with the other parameters, with events generally following two different trends. This is illustrated in Figure 3 (top panels), where the RMS values are plotted dividing the events into two subsets according to their respective behaviors. A first group of seven events (left column, Figure 3) is defined by 1) RMS increase between tests T1 and T2; 2) RMS decrease between T3 and T5 (Figure 3, top left panel). The remaining eight events (right column, Figure 3) define the second group. Since this parameter quantifies the accuracy of the fit between observed and computed first arrival times, an increase in its value upon incorporating the RSA stations suggests the presence of an issue within these data. Such an observation could be meaningful given that a decrease in RMS values is observed for the same two tests (T1 and T2) for the remaining eight events (Figure 3, top right panel).

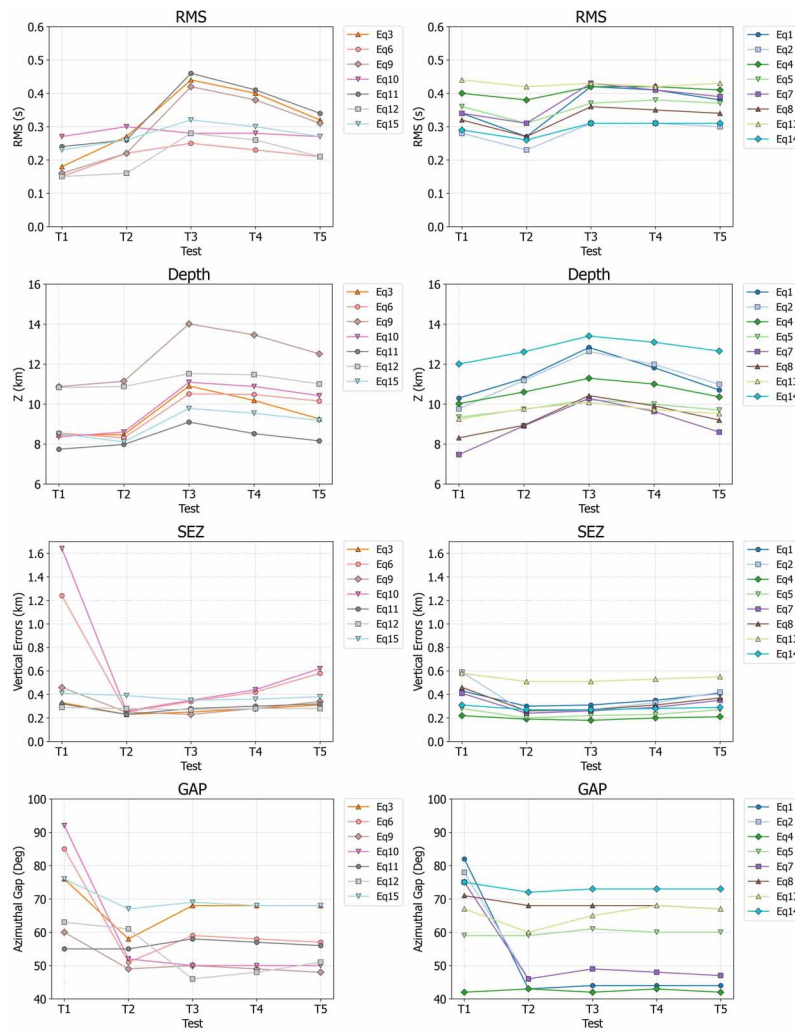


Figure 3 Earthquake localization parameters for two distinct groups of events, calculated for all tests, with corresponding markers and colors specified in the associated legend.

A comparison of the location parameters for these two groups of events reveals that the increase in the RMS values between *Test1* and *Test2*, is not related to the instrumental coverage, as the azimuthal gap drastically decreases between the two tests (T1 and T2 in Figure 3, bottom left panel). Furthermore, the increase in RMS does not appear to significantly affect the hypocentral depths, as the errors in the vertical component (SEZ) also decrease, suggesting well-constrained solutions. Station residuals were analyzed for at least three events from each group to investigate

the nature of this issue (see Figure 4 and Figure 5). For the first group, station residuals were analyzed for earthquakes 3, 6, and 9, as they show a significant variation in RMS values.

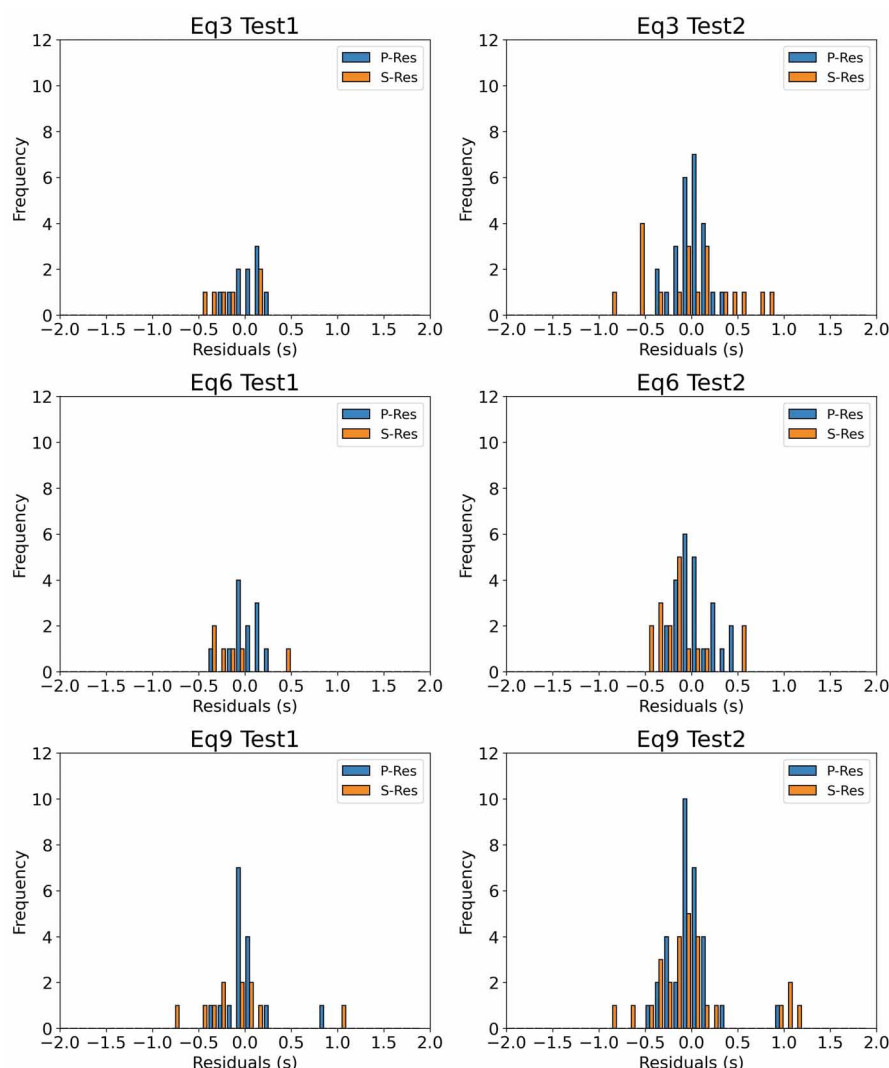


Figure 4 Station residual (s) computed for Eq3, Eq6 and Eq9 in *Test1* and *Test2*. Colors are reported in legend. These events belong to the first group of earthquakes.

As illustrated in Figure 4, the variation in the RMS values appears to be explained by the integration of the RSA stations. In fact, panels on the right in Figure 4 show the distribution of these residuals and specifically the S-phase residuals, which are mostly spread in a range from -1 to +1 seconds (see Eq3 and Eq9 in Figure 4). Furthermore, an analysis of individual stations does not reveal systematic errors associated with specific stations, suggesting that this effect is random and is primarily linked to the number of S-phase picks obtained through the automatic procedure. Nevertheless, the residuals calculated for each station remain within an acceptable range.

For the second group of events, which shows a decrease in RMS value from *Test1* to *Test2*, station residuals for events 5, 13, and 14 were investigated. Compared to *Test1*, the residuals for both P and S-phases in *Test2* still vary mostly within ± 1 s range, with S-phase residuals exhibiting a reduced spread (right panels in Figure 5), highlighting an overall better fit that explains the observed decrease of the RMS values between the two tests. Furthermore, no systematic errors were identified for specific stations, suggesting that no clock synchronization issues were present for these RSA.

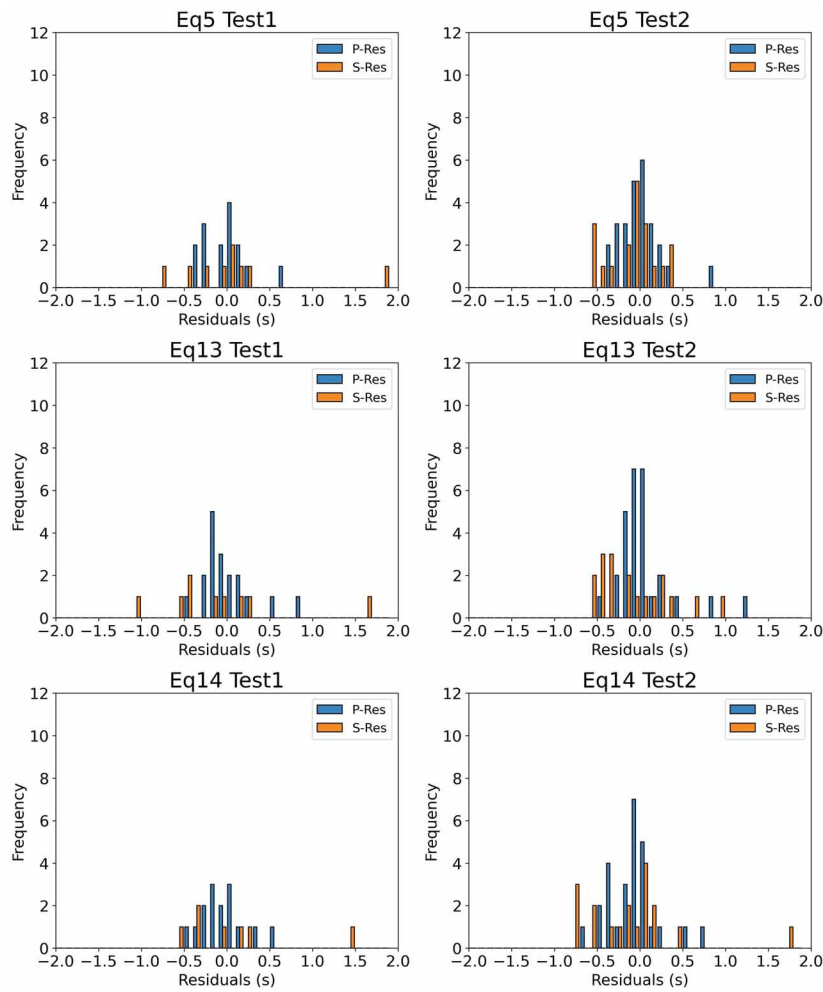


Figure 5 Station residual (s) computed for Eq5, Eq13 and Eq14 in *Test1* and *Test2*. Colors are reported in legend. These events belong to the second group of earthquakes.

However, if we consider the solution quality *S* or *QS* as defined in HYPO71 [Lee and Lahr, 1972], and so counting some ranges of RMS, SEH and SEZ, the 60% and 67% of events, respectively in *Test1* and *Test2*, are classified as B (Table 7 on the right).

	D or QD (Hypo71)						S or QS (Hypo71)				
	T1	T2	T3	T4	T5		T1	T2	T3	T4	T5
EQ1	A	A	A	A	A	EQ1	C	B	C	C	C
EQ2	B	A	A	A	A	EQ2	B	B	C	C	C
EQ3	A	A	A	A	A	EQ3	B	B	C	C	C
EQ4	A	A	A	A	A	EQ4	C	C	C	C	C
EQ5	A	A	A	A	A	EQ5	C	C	C	C	C
EQ6	B	A	A	A	A	EQ6	B	B	B	B	B
EQ7	A	A	A	A	A	EQ7	C	C	C	C	C
EQ8	A	A	A	A	A	EQ8	C	B	C	C	C
EQ9	A	A	A	A	A	EQ9	B	B	C	C	C
EQ10	B	A	A	A	A	EQ10	B	C	B	B	B
EQ11	B	A	A	A	A	EQ11	B	B	C	C	C
EQ12	A	A	A	A	A	EQ12	B	B	B	B	B
EQ13	B	B	B	B	B	EQ13	C	C	C	C	C
EQ14	A	A	A	A	A	EQ14	B	B	C	C	C
EQ15	A	A	A	A	A	EQ15	B	B	C	C	B
A	67%	93%	93%	93%	93%	B	60%	67%	20%	20%	27%
B	33%	7%	7%	7%	7%	C	40%	33%	80%	80%	73%

Table 7 Quality factors *D* (or *QD*) and *S* (*QS*) calculated for all events across each test.

Since the S , or QS , is inversely proportional to these three parameters, the percentages of events classified as B decreased from *Test3* to *Test5* due to the way this method constrains event's location (Table 7 on the right). Indeed, when applying the s - p time difference method, RMS, SEH and SEZ values increase due to the reduced number of independent P- and S-phase arrivals, the additional constraint imposed by the differential time and the associated uncertainties on the event localization (see tables A.2 in Appendix for information about these quality ranges). Stations residuals for Eq3, Eq6 and Eq9 computed across all the subsequent tests are illustrated in Figure 6.

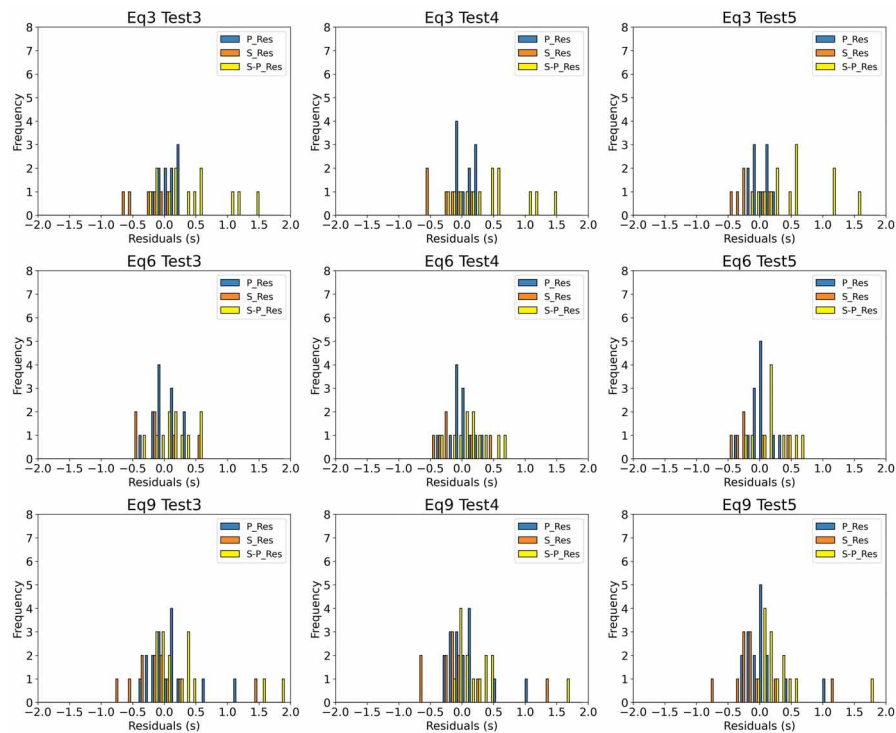


Figure 6 Station residual (s) computed for Eq3, Eq6 and Eq9 in *Test3*, *Test4* and *Test5*. Colors are reported in legend. These events belong to the first group of earthquakes.

Additionally, the residuals for ts - tp phases are also included. As previously mentioned, a reduction in the number of independent phase arrivals is evident in these three tests compared to Figure 4. Moreover, a noticeable spread toward positive values in both S-phase and ts - tp residuals is observed for all events, confirming the increase in the RMS values from *Test2* to *Test3* (see Figure 3, top left panel). However, moving from *Test3* to *Test5*, residuals become less scattered and more clustered around zero suggesting that strictly constraining the ts - tp differential time (in *Test3*) imposes a strong influence on the solution, potentially affecting its stability. Conversely, allowing a certain degree of flexibility in the estimates (*Test4* and *Test5*), enables the detection of more reliable solutions and leads to a decrease in RMS values (Figure 3, top left panel).

In contrast, an opposite trend is observed for Eq5, Eq13 and Eq14, which exhibited a decrease in the RMS values *Test1* and *Test2* (Figure 7). In *Test3*, P-, S- and ts - tp station residuals become more dispersed within the ± 1 second range, though they remain confined to that interval. This variability range impacts the RMS, causing a slight increase compared to the previous two tests. Furthermore, no clustering around zero is observed between *Test3* and *Test5*, confirming the stability of RMS values as shown in Figure 3 (top right panel). This suggests that for the events already well constrained by the initial integration of RSA data, modifying the inversion approach does not lead to significant improvements or increases in error in the solutions.

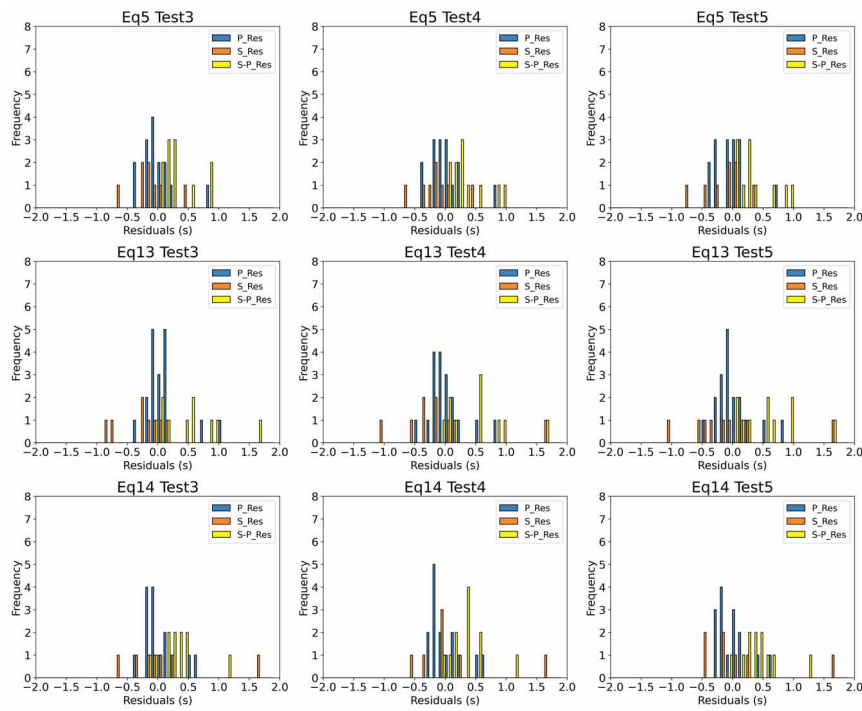


Figure 7 Station residual (s) computed for Eq5, Eq13 and Eq15 in *Test3*, *Test4* and *Test5*. Colors are reported in legend. These events belong to the second group of earthquakes.

Despite the results, all the earthquake solutions were well located, with azimuthal gaps lower than 100° , $\text{RMS} < 0.5$ s, and horizontal and vertical uncertainties not exceeding 0.8 km. The only exceptions were Eq6 and Eq10 in *Test1* (see Figures 2 and 3). The quality of the earthquake's location is also confirmed by the Hypoellipse quality factor, which is A for almost all the solutions computed across each test (Table 8). Ultimately, integration with the RSA is possible and provides high-quality estimates.

	Quality on Error Estimates (SEH and SEZ)				
	T1	T2	T3	T4	T5
EQ1	A	A	A	A	A
EQ2	A	A	A	A	A
EQ3	A	A	A	A	A
EQ4	A	A	A	A	A
EQ5	A	A	A	A	A
EQ6	A	A	A	A	A
EQ7	A	A	A	A	A
EQ8	A	A	A	A	A
EQ9	A	A	A	A	A
EQ10	B	A	A	A	A
EQ11	A	A	A	A	A
EQ12	A	A	A	A	A
EQ13	A	A	A	A	A
EQ14	A	A	A	A	A
EQ15	A	A	A	A	A
A	93%	100%	100%	100%	100%

Table 8 Hypoellipse solution's quality factor based on the least well-constrained SEH and the SEZ. Class A: $\text{SEH and SEZ} \leq 1.34$ km; B: $\text{SEH and SEZ} \leq 2.67$ km; C: $\text{SEH and SEZ} \leq 5.35$ km; D: $\text{SEH and SEZ} \geq 5.35$ km.

The integration of RSA stations into the RSN network significantly improves earthquake location accuracy by reducing azimuthal gaps and location errors. Tests show that using *ts-tp intervals* as constraints can help to overcome potentially GPS synchronization issues. However, the

variability of the location parameters depends on how strongly the constraint is applied. For the selected events, some trends are observed but no systematic station errors were detected and the quality of all the solutions turned out to be good.

In the end, RSA integration enhances network geometry and the *ts-tp* relocating approach result the best option to take into account all the potential errors, obtaining high-quality solutions that confirm the reliability of the RSA data integration.

4. Focal Mechanisms

After conducting a comparative analysis of the results for all localization tests, we assessed the influence of the RSA stations on focal plane solutions. Focal mechanisms were determined by inverting the P-wave first-motion polarities using the FocMec code [Snoke et al., 1984]. Specifically, focal mechanisms were computed for all five inversion tests; however, varying weights were applied to the polarity data based on the specifics of each test. Indeed, FocMec code allows the user to attribute an error for each discrepant polarity observation, representing the maximum allowable number of discrepant observations for a solution or based on the theoretical radiation pattern. Therefore, the error can be assigned as either an integer or a real number, according to the user's approach to accounting for these potential discrepancies.

In the second case, the code returns all the solutions with a total weight ≤ 0.1 , meaning that the number of discrepant observations may vary depending on their distance from the nodal plane within the opposite quadrant, provided their total cumulative weight does not exceed 0.1. In this study, polarity errors are weighted according to the theory of the radiation pattern to account for potential changes in the spatial distribution of stations resulting from the RSA integration and the *ts-tp* approach employed. The weight used for each event and the total number of acceptable solutions obtained, are reported in Table 9.

	Weights					N. of solutions				
	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
EQ1	0.0	0.4	0.6	0.6	0.6	193	0	141	191	201
EQ2	0.1	0.4	0.6	0.6	0.6	42	2	46	67	80
EQ3	0.0	0.2	0.3	0.3	0.3	403	37	19	40	57
EQ4	0.1	0.7	0.8	0.8	0.8	0	94	155	153	172
EQ5	0.1	0.8	0.8	0.8	0.8	45	12	0	4	7
EQ6	0.0	0.2	0.4	0.4	0.4	59	42	33	39	60
EQ7	0.0	0.2	0.4	0.4	0.4	27	16	40	53	134
EQ8	0.0	0.2	0.4	0.4	0.4	251	15	51	69	101
EQ9	0.1	0.2	0.6	0.6	0.6	279	1	4	28	108
EQ10	0.1	0.2	0.6	0.6	0.6	20	21	227	220	265
EQ11	0.1	0.8	0.8	0.8	0.8	16	28	3	11	23
EQ12	0.0	0.4	0.4	0.4	0.4	3	115	135	129	134
EQ13	0.0	0.4	0.4	0.4	0.4	40	11	13	9	11
EQ14	0.0	0.2	0.3	0.3	0.3	9	6	46	43	36
EQ15	0.0	0.2	0.3	0.3	0.3	23	23	4	8	16

Table 9 Assigned relative weights and the number of acceptable solutions obtained for all events across the inversion tests.

For the focal mechanism inversion of *Test1*, a weight of either 0.0 or 0.1 is assigned to the events. These values represent the most restrictive assignments, indicating that no discrepant polarities are accepted or, at most, only fault plane solutions with discrepant polarities on the nodal planes are considered. The choice is based on the number of RSN stations and their spatial distribution

in the central Apennines region, particularly during the period of 2007-2009. Throughout the investigated period, instrumental coverage of the Apennines was poor and uneven, with certain areas remaining entirely uncovered. Therefore, constraining the code to generate only solutions without discrepant observations represents the most suitable approach for ensuring reliable results. As shown in the first column of Figures 8 and 9, this approach enables the resolution of the earthquake source parameters for all events, except for Eq3 and Eq4 for which the focal mechanism remained unsolved or could not be determined at all.

For *Test2*, focal mechanisms were computed using a weight varying from 0.2 to 0.8. It is important to emphasize that the number of discrepant observations may vary unless their total weight does not exceed the assigned threshold. Increasing the weight was necessary for this test due to the growing number of stations. Integrating RSN with RSA data enhances the likelihood of discrepancies, particularly in station clusters near the nodal plane. Therefore, increasing the weight enhances the likelihood of identifying a valid solution. Integrating RSA data improves the kinematic constraints for most events (except for Eq1), as observed for Eq3, Eq6, and Eq8.

Focal mechanisms for *Test3*, *Test4* and *Test5* were computed using the same increased weight, with values ranging from 0.3 to 0.8 per event. The decision to maintain a consistent weight across the three tests is justified because they were all processed using the same approach, differing only in the weight assigned to the *ts-tp* time interval. Compared to *Test2*, the results in *Test3* were well resolved. Although the solutions remained well resolved in *Tests4* and *Test5*, they became progressively less constrained. This behavior is related to the progressive increased weight of the *ts-tp* interval. In *Test5* the weight assigned to the *ts-tp* differential time is the highest, introducing a certain degree of flexibility in the solutions and an increase in the acceptable solutions (see Figures 8 and 9 and Table 9).

Overall, the solutions obtained from *Tests2* to *Test5* are consistent with each other, except for Eq9 (Figures 9). However, this event already exhibits high RMS values and significant variations in depth (Figure 3), so further investigations are required for this earthquake.

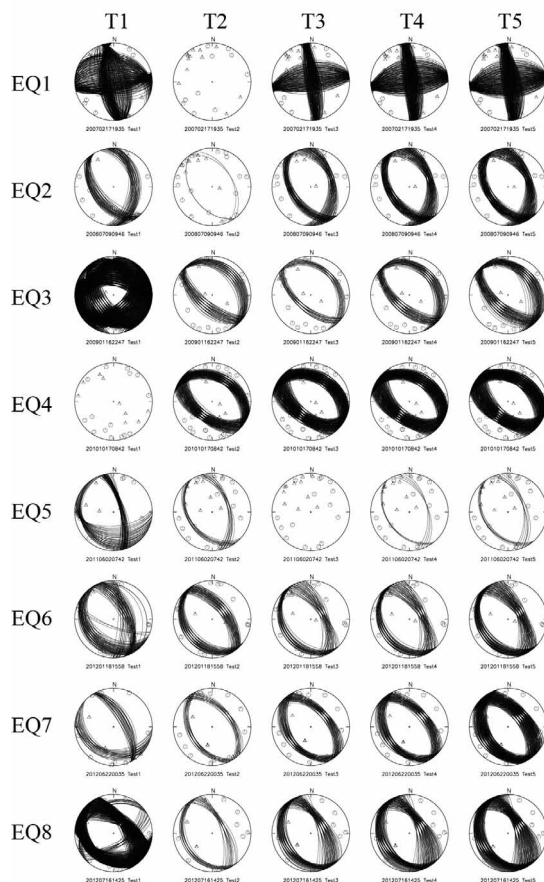
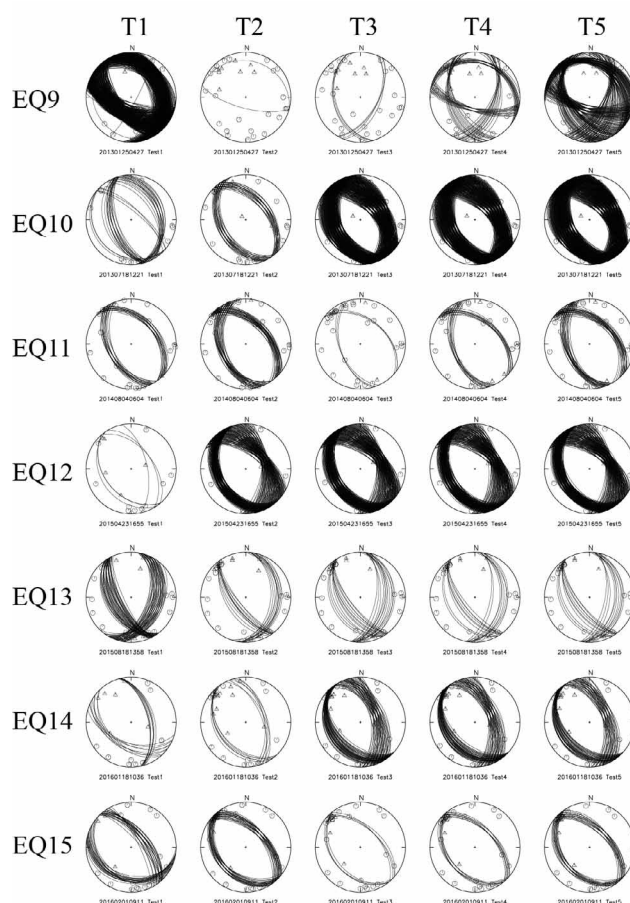


Figure 8 Focal mechanisms solutions computed using the weight reported in Table 9.

Figure 9 Focal mechanisms solutions computed using the weight reported in Table 9.



5. Final Considerations

In this study, RSA data were examined and integrated with RSN data to enhance the localization and kinematic information of 15 small-magnitude events. Since some of the RSA data are affected by clock synchronization errors, determining the optimal approach for utilizing these data became a primary objective. The data under analysis presents numerous challenges, some of which are difficult to identify or quantify. Given all the uncertainties, the most effective approach was to assume that all data were affected by the same synchronization issue and treat them consistently. Thus, five relocation trials were performed using the same velocity model. For each test, focal mechanisms were computed using a consistent approach, with slight variations in the weight assigned to the inversion based on the characteristics of the tests.

The results demonstrate that integrating the RSA data improved the earthquake locations by reducing errors and better constraining hypocentral depths. Moreover, the focal mechanism solutions were consistent for each event across all tests from *Test2* to *Test5*, further validating the contribution of RSA data integration. Among all the trials conducted, the most effective approach was found to be using the *s-p* differential time to locate the events, assigning it a weight of 2. Indeed, the results from *Test5* were the most accurate, as they accounted for all potential sources of error while allowing for a reasonable margin of uncertainty in the estimates provided. By applying the procedure to locate all the RSA data, it would be possible to easily integrate them into most analyses, thereby enhancing the resolution of smaller events. Moreover, given that the RSA stations have collected data for nearly 30 years, their integration can offer valuable insights into the seismic sequences in the central Apennines, enhancing our understanding of regional seismic activity.

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APPENDIX

A.1 – Tables of the default weights along with the corresponding standard error (in seconds), as specified in Hypoellipse manual [Lahr J.C., 1989].

STANDARD ERROR (s)	WEIGHT-CODE
0.1	0
0.5	1
1.0	2
2.0	3
INFINITE	4

A.2 – Tables of the criteria used for defining the QS and QD quality factors, as defined in HYPO71 [Lee and Lahr, 1972].

QS	RMS (s)	SEH (km)	SEZ (km)	QD	No.	GAP	Dmin
A	< 0.15	≤ 1.0	≤ 2.0	A	≥ 6	≤ 90°	≤ Z or 5 km
B	< 0.30	≤ 2.5	≤ 5.0	B	≥ 6	≤ 135°	≤ 2*Z or 10 km
C	< 0.50	≤ 5.0		C	≥ 6	≤ 180°	≤ 50 km
D	Others			D	Others		

- RMS: Root mean square of the solution. This value is a time and is expressed in seconds;
- SEH: Represent the 68% confidence limit for the horizontal component. For quality classification, the least well-constrained direction among the two SEH values provided by the Hypoellipse code is considered. This value is expressed in kilometers;
- SEZ: Represent the 68% confidence limit for the vertical component (hypocentral depth). This value is expressed in kilometers;
- No.: Number of P- and S-phases used for the localization process;
- GAP: Azimuthal gap. This value represents an angle and is expressed in degrees;
- Dmin: Minimum distance between the epicenter and the closest seismic station which is recording. This value represents a distance and is expressed in kilometers.



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