

1 **Accessing European Strong-Motion Data: an update on ORFEUS Coordinated**
2 **Services.**

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4 G. Lanzano(*)¹, L. Luzi¹, C. Cauzzi², J. Bienkowski³, D. Bindi⁴, J. Clinton⁵, M. Cocco⁶, M. D'Amico¹,
5 J. Douglas⁷, L. Faenza¹, C. Felicetta¹, F. Gallovič⁸, D. Giardini⁹, O.-J. Ktenidou¹⁰, V. Lauciani¹, M.
6 Manakou¹¹, A. Marmureanu¹², E. Maufroy¹³, A. Michelini¹, H. Özener¹⁴, R. Puglia¹, R. Rupakhety¹⁵,
7 E. Russo¹, M. Shahvar¹⁶, R. Sleeman³, N. Theodoulidis¹⁷.

8
9 (*) Corresponding author

- 10
11 1. Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy
12 2. ORFEUS and Swiss Seismological Service at ETH Zurich, Switzerland
13 3. Koninklijk Nederlands Meteorologisch Instituut (KNMI), Netherlands
14 4. German Research Centre for Geosciences (GFZ), Germany
15 5. Swiss Seismological Service at ETH Zurich, Switzerland
16 6. EPOS ERIC and Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy
17 7. University of Strathclyde, United Kingdom
18 8. Charles University in Prague, Czech Republic
19 9. ETH Zurich, Switzerland
20 10. National Observatory of Athens (NOA), Greece
21 11. Aristotle University of Thessaloniki (AUTH), Greece
22 12. National Institute for Earth Physics (NIEP), Romania
23 13. Université Grenoble Alpes, France
24 14. Boğaziçi University, Kandilli Observatory and Earthquake Research Institute
25 (KOERI), Turkey

26 15. University of Iceland, Iceland

27 16. Road, Housing & Urban Development Research Center (BHRC), Iran

28 17. Institute of Engineering Seismology and Earthquake Engineering (ITSAK), Greece

29

30 **Abstract:**

31 Strong ground-motion records and free open access to strong-motion data repositories are
32 fundamental inputs to seismology, engineering seismology, soil dynamics, and earthquake
33 engineering science and practice. This paper presents the current status and outlook of the ORFEUS
34 (Observatories & Research Facilities for European Seismology) coordinated strong-motion
35 seismology services, namely the Rapid Raw Strong Motion (RRSM) and the Engineering Strong
36 Motion (ESM) databases and associated web interfaces and web services. We compare and discuss
37 the role and use of these two systems using the M_w 6.5 Norcia (Central Italy) earthquake that occurred
38 on October 30, 2016 as an example of a well-recorded earthquake that triggered major interest in the
39 seismological and earthquake engineering communities. The RRSM is a fully automated system for
40 rapid dissemination of earthquake shaking information, while the ESM provides quality-checked,
41 manually processed waveforms and reviewed earthquake information. The RRSM uses only data
42 from EIDA (the European Integrated Waveform Data Archive), while the ESM includes also offline
43 data from other sources, such as the Italian strong-motion database ITACA. Advanced software tools
44 are also included in the ESM to allow users to process strong-motion data and to select ground-motion
45 waveform sets for seismic structural analyses. The RRSM and ESM are complementary services
46 designed for a variety of possible stakeholders, ranging from scientists to the educated general public.
47 The RRSM and ESM are developed, organized and reviewed by selected members of the
48 seismological community in Europe, including strong-motion data providers and expert users. Global
49 access and usage of the data is encouraged. The ESM is presently the reference database for
50 harmonised seismic hazard and risk studies in Europe. ORFEUS strong-motion data are open, *FAIR*,

51 and accompanied by licencing information. The users are encouraged to properly cite the data
52 providers, preferably using seismic network DOIs (Digital Object Identifiers).

53

54 **Introduction & motivation**

55 ORFEUS (Observatories & Research Facilities for European Seismology; see *Data and Resources*)
56 is a collaborative effort that coordinates observational seismology across the greater European region
57 through the collection, archiving and dissemination of seismic waveform data, metadata and closely
58 related products. Since 2013, ORFEUS has promoted the European Integrated waveform Data
59 Archive (EIDA) program, which provides timely access to seismic data archives with a focus on
60 broadband (velocity) data (Strollo et al., this Focus Section; see *Data and Resources*). In 2014,
61 ORFEUS formally added a second program, focusing on strong-motion seismology, to its existing
62 EIDA branch. This new program integrates two main services: (a) an automatic, rapid, raw strong-
63 motion database (RRSM; see *Data and Resources*), which operates in near real-time, based on
64 waveforms and metadata available on EIDA; and (b) a manually verified, expert revised engineering
65 strong-motion database (ESM; see *Data and Resources*), which integrates data available from EIDA
66 as well as other strong-motion agencies or observatories in the Euro-Mediterranean region. The
67 RRSM and ESM services are integrated in the framework of the EPOS Thematic Core Service for
68 Seismology (Figure 1). There are about 7,600 Euro-Mediterranean earthquakes and 54,500 manually
69 processed waveforms in the ESM for the period 1967-2020; for the last 10 years, there are 7,700+
70 earthquakes in the RRSM, of which ~ 960 have been added during the last 12 months.

71 Much work has been carried out by ORFEUS during the last decade to encourage the adoption of
72 international seismological community standards within strong-motion seismology. This is partly
73 achieved by promoting coordinated activities among the key strong-motion data providers operating
74 in the greater European region within the ORFEUS Strong-Motion Committee. The main goal of this
75 group is to encourage and enable open and FAIR ('Findable, Accessible, Interoperable and
76 Reusable', after Wilkinson et al., 2016) access to event-based waveforms, derived intensity measures
77 and downstream products. Technical and scientific feedback on activities and services of this
78 committee is ensured through a User Advisory Group composed of selected members of the users'

79 community. The strong-motion infrastructures promoted by ORFEUS were originally rolled out in
80 2015 (Luzi et al., 2016; Cauzzi et al., 2016), and have since witnessed major modernization and
81 upgrades, chiefly centered around web services and augmented station and/or site information.

82 The aim of this Focus Section article is to provide an update on the current status and outlook of these
83 research infrastructures, and to encourage wide use of the open-access dataset. We also stress the
84 importance of proper acknowledgment of the data providers that are the basis of this service.

85 In the sections that follow, we introduce the key features of the RRSM and ESM with emphasis on
86 recent developments (new web interfaces, new standard and *ad-hoc* web services, additional
87 earthquake and site information, amongst others). The well-recorded M_w 6.5 Norcia earthquake,
88 occurred on October 30, 2016, in Central Italy, is used as an example to compare and discuss the two
89 systems.

90

91 **The ORFEUS Rapid Raw Strong Motion (RRSM) system**

92 October 30, 2016 - 06:40:18 UTC. It is early morning in Italy when a severe earthquake – the largest
93 (M_w 6.5) of a long sequence (Chiaraluce et al., 2017) that has been ongoing for a few months – hits
94 the central Apennines. The shaking is felt across most of the Italian peninsula and surrounding
95 regions. The damage is major and widespread. Luckily there are no victims: most of the affected areas
96 had been evacuated after two significant events occurred on October 26, and had suffered damaging
97 earthquakes in the (recent) past, resulting in the adoption of stronger seismic criteria in previous
98 reconstructions (Mazzoni et al., 2018). Within minutes, national and international seismological
99 agencies in Europe locate the event and estimate its magnitude. The Euro-Mediterranean
100 Seismological Centre (EMSC; see *Data and Resources*) locates the M_w 6.5 earthquake within 10 km
101 of the town of Norcia and assigns it a unique event identifier (ID, equal to 20161030_0000029). As
102 soon as this information becomes available, an automatic procedure is triggered at the ORFEUS
103 datacenter in the Netherlands to retrieve and process all the data available in near real-time from

104 EIDA. The available on-scale data (both velocity and acceleration waveforms) are processed by the
105 software module *scwfparam* (Cauzzi et al., 2016), integrated in the free open-source SeisComP3
106 distribution (Hanka et al., 2010; see *Data and Resources*). Within 10-20 minutes of the earthquake
107 origin time, web pages are automatically generated showing recorded peak motions and response
108 spectra for all the recordings matching pre-defined quality criteria (Cauzzi et al., 2016). Event
109 information, raw waveforms and station metadata are also made available via standard FDSN
110 *dataselect* and *station* web services (see *Data and Resources*), while processed waveforms, peak-
111 motion data and response spectra are revealed via *ad-hoc* web services (Figure 2; Table 1), providing
112 also the formatted input to the USGS ShakeMap software (Worden et al., 2020). To ensure the
113 inclusion of delayed data, the processing will be repeated according to a predefined schedule that
114 spans one week after the earthquake nucleation time (processing and re-processing namely follows
115 this scheduling: five minutes; 15 minutes; one hour; three hours; six hours; one day; two days; one
116 week after nucleation time).

117 The aforementioned set of automatic, predefined operations illustrates how event and waveform
118 parameter information is added to the Rapid Raw Strong-Motion (RRSM) system (Cauzzi et al.,
119 2016), a European service maintained and coordinated by ORFEUS and integrated in the European
120 Plate Observing System (EPOS; see *Data and Resources*). The main goal of the RRSM is to provide
121 a rapid summary of the openly available strong-motion data to the scientific and technical community,
122 which is often keen to quickly, openly, collaboratively access all the available data to contribute to
123 the scientific discussion on major earthquakes and their impacts. The RRSM also provides elements
124 of situational awareness to the general public and rapid response agencies, alongside other national
125 and international natural hazard information systems. The RRSM system is configured to process all
126 on-scale waveforms generated by Euro-Mediterranean ($27^{\circ} \leq \text{latitude} \leq 81^{\circ}$, $-32^{\circ} \leq \text{longitude} \leq 51^{\circ}$)
127 earthquakes with magnitude (using any scale reported by EMSC) larger than 3.5, store basic and
128 processed information in a database, and display and disseminate the waveform data, metadata and
129 derived products using state-of-the-art web interfaces and web services. The RRSM was originally

130 conceived to serve a broad community of stakeholders, ranging from strong-motion seismologists to
131 the educated general public, and was inspired by the Japanese strong-motion portals (National
132 Research Institute for Earth Science and Disaster Resilience, 2019; see *Data and Resources*), where
133 unprocessed seismic data and derived products are made available rapidly and with open access. The
134 RRSM provides information on the number of available seismic recordings and includes information
135 on the key features, therefore informing the users on the significance of the earthquakes and
136 associated data. All RRSM data are available without any requirement of logging into the system.
137 The most important improvements implemented in the RRSM system since its first release (Cauzzi
138 et al., 2016) are, in terms of platform functionality: (a) a new web interface that replaces OpenCMS
139 with Django 3.0 (see *Data and Resources*), which is free and open-source; (b) enhanced content of
140 the web interface which is now fully supported by dynamic web services and also made available in
141 json and text formats. In addition to this environment upgrade, automatic detection of outliers has
142 been improved since the initial design of the system, and new quality-control metrics are being
143 considered based on user feedback. Among the new quality checks are: (a) comparing peak-motion
144 parameters between components at each station; (b) comparing peak-motion parameters between
145 neighbouring stations; (c) comparing the recorded peak-motion with a reference ground motion
146 prediction model for Europe. Even so, RRSM data should be used with caution, because they result
147 from purely automatic processing without any manual review. Expert revision of event metadata,
148 ground-motion data and metadata is the focus of the Engineering Strong-Motion (ESM) database /
149 system, described in the following Section.

150

151 **The Engineering Strong-Motion (ESM) database: a community effort promoted by ORFEUS**

152 The Engineering Strong-Motion Database (ESM; Luzi et al., 2016) is a research infrastructure that
153 encloses a set of facilities to store, search, select, download and process ground-motion data and
154 associated metadata. The ESM is specifically tailored to serve engineers and earth scientists in the
155 assessment of seismic hazard and risk, because it provides end users with three-component, quality-

156 checked, uniformly and manually processed strong-motion waveforms from events with magnitude
157 larger than 4.0 (any scale) in the greater European region. ESM is continuously populated by
158 processed waveforms gathered from EIDA and by offline data coming from regional databases, such
159 as the ITalian ACcelerometric Archive (ITACA, Pacor et al. 2011; see *Data and Resources*).

160 From the publication of the first release of the web interface (see *Data and Resources*) in 2015, the
161 ESM database has become increasingly popular (Figure 3); starting with fewer than 100 unique
162 visitors per month in January 2015, the number of visitors has been increasing until 10,000 in the
163 second half of 2016, following the M_w 6.2 Amatrice earthquake. In the observation period from May
164 2017 to March 2020, the average monthly number of visits to the ESM website is about 2,600, while
165 the unique visitors are about 1,200. The requests are on average 96,000 per month, with a peak of
166 more than 300,000 hits in January 2017, during the 2016-2017 Central Italy sequence. The amount
167 of data downloaded (Figure 3b) experienced a first significant increment during the 2016-2017
168 Central Italy sequence; a second significant peak of 200GB is also observed in the second half of
169 2019.

170 Currently, ESM is developed and maintained by a dedicated working group of INGV (Istituto
171 Nazionale di Geofisica e Vulcanologia, Italy) under the coordination of the ORFEUS strong-motion
172 committee, with a short-term plan to involve members of all the contributing agencies in the manual
173 processing of the ESM data. A major process of renewal of the ESM has been carried out in the last
174 three years, leading in July 2020 to the release of the new ESM website (Luzi et al. 2020; see *Data
175 and Resources*). The main changes included: a) the ESM web frontend was renewed to better support
176 user needs, both in terms of content and speed / performance; b) the database structure was modified
177 to archive supplementary information; c) OpenStreetMap was adopted for the visualization of
178 geographic objects; and d) the internal authentication system was updated to allow access through
179 Google and ORCID credentials. Anonymous users are allowed to explore the website and view the
180 metadata, whereas authenticated users can also access time-series plots, download waveforms and
181 use all ESM products and tools. The new database management system avails of PostgreSQL (see

182 *Data and Resources*), while the back-end software is developed in Python: the database structure is
183 specifically designed to collect multiple sets of metadata associated with events and stations. The
184 same parameter (e.g. the earthquake magnitude) can have several estimates according to different
185 sources / agencies, and the most reliable value (based on expert judgment) is indicated as preferred.
186 The new ESM website is still organized in three main blocks (Luzi et al. 2016), associated with
187 “Events”, “Stations” and “Waveforms”. In addition, several pages are dedicated to the supporting
188 documentation (block “Documents”), such as User manuals, Tutorials, Links, FAQs and scientific
189 documentation. In the following, we present the major features related to these blocks and the main
190 novelties related to the additional tools, such as waveform processing and web services.

191

192 *Events*

193 Seismic events can be retrieved by accessing the “Events” page of the portal (Figure 4). The user can
194 search for events using multiple key parameters, including origin date and time, magnitude range,
195 hypocentral coordinates, and style of faulting. Additional selection criteria are available such as
196 searching for a single recording network or station. The query returns a list of earthquakes that can
197 be individually accessed. As of December 2020, there are about 7,600 events included in the
198 European and Middle East area, covering a moment magnitude range from 3.3 to 7.8 (see *Data and*
199 *Resources* for data summary and statistics are accessible).

200 When an event is selected from the list, the user is redirected to the event-specific page, where the
201 earthquake metadata are grouped into sub-sections: a) Origin; b) Moment tensor; c) Source; d)
202 Records; e) Shake map. In Figure 5, an example is given for the M_w 6.5 Norcia earthquake (ESM ID:
203 EMSC-20161030_0000029).

204 The “Origin” section reports the event identifiers assigned by different authoritative sources (EMSC,
205 ISC, USGS, and INGV), the location of the event, and the estimates of local and moment magnitude.

206 The “Moment tensor” section shows the moment tensor solutions (seismic moment, nodal planes),
207 including the beachball representation. The “Source” section contains information on the geometry

208 of the causative fault and the coordinates of the nucleation point. The “Shake map” section shows the
209 INGV ShakeMap for Italy (Michellini et al., 2008; Michellini et al. 2020) and the USGS ShakeMap
210 (Wald, 2000) outside Italy in terms of Peak Ground Acceleration (PGA), Peak Ground Velocity
211 (PGV), and Spectral Acceleration (SA) at periods 0.3, 1, and 3 s. In the “Records” section, the list of
212 available waveforms is provided and data can be downloaded upon registration.

213

214 *Stations*

215 The station information can be accessed by entering the “Stations” page, where recording sites can
216 be retrieved according to location, network, station code, and several parameters related to site
217 characterization, such as the time-averaged shear-wave velocity in the uppermost 30 m ($V_{S,30}$).
218 Additional selection criteria are the number of records per station and the availability of the geologic
219 map. To date (December 2020), the number of stations in Europe and the Middle East in ESM is
220 almost 3,500.

221 Station web-pages are arranged into eight tabs (Figure 6), namely: a) Station info; b) Topography; c)
222 Geothematic Maps; d) Geotech-Geophys data (example in Figure 4 for NRC station); e)
223 Seismological Analysis; f) Records; g) Photo gallery; h) Documentation. The “Station info” section
224 contains summary information about the recording station, such as the network and station code,
225 station location, installation/removal dates, installation type and preferred parameters for site
226 characterization, i.e. $V_{S,30}$ and site category according to Eurocode 8 (CEN, 2004). The fundamental
227 information to estimate the seismic site response according to Felicetta et al. (2017), are: a) S-wave
228 velocity profile or microtremor analysis in the “Geotech-Geophys data” section; b) correlation with
229 surface geology in “Geothematic Maps”; and c) correlation with slope angle (Wald and Allen, 2007)
230 in “Topography”.

231 The new section entitled “Seismological Analysis” contains a set of Horizontal-to-Vertical spectral
232 ratios (Lermo & Chavez-Garcia, 1993) evaluated as per Puglia et al. (2011) and obtained from: a)
233 5%-damped acceleration (linear) response spectra (HVRS); b) S-phase acceleration Fourier

234 amplitude spectra (S-PHASE HVSR); and c) coda acceleration Fourier amplitude spectra (CODA
235 HVSR). The list of waveforms recorded by the selected station is available in the “Records” section
236 and each observation can be downloaded upon registration. The “Photo gallery” section compiles
237 photos of the recording station, displaying housing and instrumentation, while the “Documentation”
238 section provides any external documents relative to the recording site.

239

240 *Waveforms*

241 In the “Waveforms” page, several parameters can be specified as selection criteria, mostly related to
242 stations, events, or waveform metadata. With respect to the previous ESM release, new selection
243 parameters are now available, such as a flag for waveforms with pulse-like behavior (Shahi and
244 Baker, 2014). Once the selection criteria are set, the user can also export a parametric table (‘flatfile’)
245 which contains relevant parameters and metadata for seismological and engineering applications;
246 such output is important, for instance, for ground-motion model development (e.g., Kotha et al., 2020;
247 Lanzano and Luzi, 2020). The total number of waveforms available in the database is about 76,000
248 (December 2020), of which about 54,500 (72%) are manually processed and reviewed.

249 Time series can be visualized and downloaded upon user registration. The waveform visualization
250 has a new layout that allows zooming and exporting time series as images; the download formats
251 allow the user to obtain data in the form of unprocessed acceleration time series and of processed
252 acceleration, velocity, and displacement time series. Fourier (Figure 7) amplitude spectra and
253 acceleration and displacement elastic 5%-damped response spectra calculated at 105 oscillation
254 periods (0.01–10 s) are also available for download. The available export formats are ASCII and
255 Adaptable Seismic Data Format (ASDF) as per Krischer et al. (2016), the latter being a binary
256 standard intended for researchers and analysts. In the “User Manuals” section, the user can find
257 additional details on how to open/process/convert the files. The “Download” sub-section also
258 provides the full licensing and acknowledgments information that users need in order to properly cite
259 the data.

260

261 *Additional tools*

262 ESM also provides machine-friendly access to data, metadata and tools included in the database
263 through web services (WSs). The available WSs are listed in Table 2.

264 The “Token”, “Event”, “Station” and “Data-download” WSs require prior installation of any program
265 supporting the HTTP-POST method, e.g. CURL (see *Data and Resources*). To call the “Event”,
266 “Station” and “Data-download” WSs, the user should first authenticate by compiling the ESM
267 registration form, and then use the “Token” WS to begin with. The “Station” WS provides a subset
268 of station metadata in the FDSN StationXML standard (see *Data and Resources*); the “Event” WS
269 provides the event metadata in QuakeML format (Schorlemmer et al. 2011; see *Data and Resources*);
270 the “Data-download” WS allows the user to download time series and response spectra in ASCII or
271 ASDF formats. The “ShakeMaps” WS returns the input file for the generation of USGS-style
272 ShakeMaps and does not require authentication; instead, it can be executed directly by url.

273 Another set of WSs are related to REXELweb (Sgobba et al., 2019), a tool for the automatic selection
274 and scaling of spectrum-compatible accelerograms for engineering applications. REXELweb is
275 temporarily provided as an executable application developed in the MATLAB® environment, while
276 an interactive web interface will be released in early 2021.

277 Additional ESM tools and products include the web interface for processing and the ESM flatfile. A
278 renewed web interface for the strong-motion processing service (Puglia et al. 2018; see *Data and*
279 *Resources*) is now integrated in ESM (see *Data and Resources*). It was adapted for the new website
280 by adding new options, while maintaining the same functionalities. The service adopts a processing
281 scheme (Pacor et al., 2011; Paolucci et al., 2011) that has been extensively tested (Boore et al. 2012).
282 This service allows direct access to the dataset contained in the ESM database. The tool’s target
283 audience comprises engineering seismologists, earthquake engineers, as well as students and
284 practitioners, since it allows the user to save and download the processed data for use in other
285 applications.

286 The webpage of the ESM flatfile (Lanzano et al., 2019 & 2020; Bindi et al., 2019) has been integrated
287 in the ESM website under the “Products” section. It consists of a parametric table containing verified
288 and reliable metadata and intensity measures of manually processed waveforms included in the
289 database. Aimed at collecting strong-motion data and related metadata in a uniform, updated,
290 traceable and quality-assured way, the ESM flatfile was the reference to update the ground-motion
291 model and logic tree to be used in the new harmonised seismic hazard model of Europe (Bindi &
292 Kotha, 2020; Kotha et al., 2020; Weatherill et al., 2020; Weatherill & Cotton, 2020), developed within
293 the EC-funded project SERA and disseminated by EFEHR (European facilities for Earthquake hazard
294 and Risk; see *Data and Resources*), the hazard and risk component of EPOS Seismology (see *Data*
295 *and Resources*).

296

297 **Comparison of RRSM and ESM data using ShakeMaps**

298 In this section, we use ShakeMaps to compare and discuss the data available through the RRSM and
299 ESM databases for the Norcia 2016 earthquake, which was already used as an example in the previous
300 Sections. To this end, we have adopted the new version (v4.0) of the USGS-ShakeMap software
301 (Worden et al., 2020) using the configuration recently provided for Italy by Michelini et al. (2020).
302 The data were downloaded using the ShakeMap web services listed in Table 1 and Table 2. The data
303 downloaded from RRSM include peak ground motion parameters (PGA, PGV) and spectral
304 accelerations values at $T=0.3$, 1.0 and 3.0 s from 121 strong-motion stations. Data from about twice
305 as many stations (233) have been downloaded from ESM. For this event, note that the ESM contains
306 a large number of off-line strong-motion recordings acquired by the Italian Accelerometric Network
307 (RAN; PCM, 1972), which is not included in EIDA. For the sake of conciseness, in Figures 8 and 9
308 we only show maps of intensity and PGA, respectively (other typical products of ShakeMap are maps
309 of peak ground velocity and spectral acceleration at selected vibrations periods, and ground motion
310 attenuation plots). The maps shown in Figures 8 and 9 display the results obtained with the RRSM
311 data set only and those with two data sets merged together featuring a total of 314 stations total. To

312 the purpose of comparison, we also show the differences between the ShakeMaps obtained using the
313 two data sets configurations. The maps generated using the two datasets differ in the number of
314 observations, the earthquake location and the presence or absence of the finite fault geometry
315 (Chiaraluce et al., 2017).

316 In this specific case, we see that the maps obtained using RRSM data tend to yield lower values of
317 shaking to the North-West of the earthquake source (Figures 8c and 9c). This is mainly due to the
318 smaller number of strong-motion observations available in RRSM. Even without the presence of the
319 finite fault (Fig. 8a and 9a), the near-source shaking levels obtained using the near-real-time RRSM
320 data are generally consistent with those shown in the final ESM map (cf the 20% and 50% g contour
321 lines in Fig. 9a and 9b), although the RRSM dataset alone cannot not provide the same spatial
322 resolution and amount of information of the combined one. Indeed, as shown in Cauzzi et al. (2016),
323 the peak-motion values provided by ESM and RRSM for the events and stations available in both
324 databases are very similar, in spite of any differences between the automatic and manual processing
325 schemes. Yet, it can still occur that in isolated instances the results of the automatic data processing
326 can differ from the outcome of the manual revision. An example in our case is represented by the
327 anomalously low peak-motion values at station ‘INTR’ (13.9046, 42.0115; at ~ 110 km epicentral
328 distance) which is responsible for the large localized anomaly of the MCS intensity field observable
329 in Figure 8c: the recordings of this station contribute to the RRSM dataset, but were excluded from
330 the ESM revised one. The lower shaking values in the RRSM ShakeMap can also derive from
331 different magnitude bias corrections applied to both maps indeed depending on the set of observations
332 available. Regarding the different earthquake locations adopted when generating the maps with the
333 two datasets, they do not appear to produce significant differences, at least at the scale of these maps.
334

335 **Conclusions and future developments**

336 The RRSM and ESM platforms are complementary community-coordinated and therefore unique
337 examples of data access in the domain of strong-motion seismology. Like all products promoted by

338 ORFEUS, they rely on the (largely in-kind) support of a dense network (continuously being
339 expanded) of data providers and scientists, who often play the roles of both users and contributors /
340 developers of the databases and associated services. Data acquisition and software development
341 mainly occur at local and national strong-motion agencies - most of which are members of ORFEUS
342 - while ORFEUS is in charge of further advertising and of promoting open access to the data and
343 adoption of standard best practices in data management. Contributing to ORFEUS-coordinated data
344 archives has clear advantages for the data providers, including long-term archival, state-of-the-art
345 quality control, improved access and increased usage of waveform data and metadata, enhanced
346 visibility, and community support.

347 The RRSM and ESM operate as complementary services on two different time scales. The RRSM
348 provides automatic information that is crucial within the first few hours or days after the earthquake
349 occurrence. Once manual processing is completed (typically within a few days or weeks, depending
350 on the relevance of the earthquake and the number of waveforms available), the ESM becomes the
351 authoritative source of information. The ESM is dynamically updated as new information (e.g. the
352 geometry of the causative fault) becomes available, while RRSM re-processing schedule will stop
353 one week after the earthquake occurrence. The RRSM uses only on-scale high-sampling-rate data
354 from EIDA (the European Integrated Waveform Data Archive), while the ESM includes also off-line
355 strong-motion data from other sources. The strong-motion data web page at ORFEUS (see *Data and*
356 *Resources*) provides automatic redirection to the RRSM or ESM, depending on whether the event
357 data have been manually reviewed or not. The RRSM and ESM peak-motion web services provide
358 key input to an ongoing community effort to harmonise ShakeMaps in Europe (Cauzzi et al., 2018),
359 with emphasis on: (i) promoting cross-border collaboration and homogenisation of ShakeMap
360 production; (ii) providing a backup to local authoritative ShakeMap implementations; and (iii)
361 delivering ShakeMaps for regions where no local capability is yet available.

362 The RRSM and ESM data are open and FAIR (Wilkinson et al., 2016). Since the RRSM uses only
363 data available on EIDA, the ORFEUS-EIDA data policy and disclaimer is valid for the RRSM data

364 (see *Data and Resources*). The majority of EIDA waveform data are made available under a CC:BY
365 4.0 licence (i.e., the user can copy and redistribute the material in any medium or format and remix,
366 transform, and build upon the material for any purpose, even commercially), and users are encouraged
367 to provide proper reference to the data suppliers, preferably by using network DOIs where available.
368 Some ESM services require authentication, however neither restrictions nor embargo times apply to
369 the data. ESM data are also accompanied by licencing (generally CC BY 4.0 or CC BY NC 4.0) and
370 citation information. Users of ORFEUS strong-motion services are encouraged to properly cite the
371 data providers, preferably using seismic network DOIs (see *Data and Resources*). We encourage
372 global access to and usage of the data. This will be facilitated by providing a variety of formats in
373 ESM, including the COSMOS strong-motion data formats popular in the engineering community.
374 Other international strong-motion initiatives (e.g., global USGS ShakeMaps, COSMOS) are also
375 welcome to make use of ORFEUS distributed data following the provided licencing and
376 acknowledgment policies. We note that ORFEUS RRSM and ESM web services and web pages can
377 be easily featured as links in the portals of other agencies, with no need to locally replicate the data
378 archives.

379 The RRSM and ESM systems will continue to improve and evolve towards a largely homogeneous
380 and fully complementary system. One critical action to be undertaken in this direction is the automatic
381 inclusion of on-scale velocity data and lower-magnitude events in the ESM. This requires a strategic
382 decision presently being discussed within the ORFEUS Strong-Motion Committee and the strong-
383 motion community at large, as well as technical developments (e.g., homogeneous processing
384 software including automated quality control, database performance assessment) that will likely
385 require allocating significant resources in the coming years.

386

387 **Data and Resources**

388 The website of ORFEUS is accessible at <http://www.orfeus-eu.org/>. The websites of the research
389 infrastructures managed by the ORFEUS Strong-Motion Committee are: <http://www.orfeus->

390 eu.org/rrsm/index.html for the RRSM; <https://esm-db.eu> for the new ESM; <https://esm.mi.ingv.it> for
391 the now deprecated previous release of the ESM. Waveforms and metadata used by the RRSM and
392 ESM are available through EIDA at [http://www.orfeus- eu.org/data/eida](http://www.orfeus-eu.org/data/eida). ESM also benefits from
393 other public web services and includes off-line waveforms that are fully acknowledged in Luzi et al.
394 (2016). In particular, additional ESM records of the M_w 6.5 Norcia earthquake used in this paper were
395 obtained from the Italian ACcelerometric Archive (ITACA, <http://itaca.mi.ingv.it>). Django is
396 described at <https://www.djangoproject.com/>. OpenCMS is described at
397 <http://www.opencms.org/en/>. The Strong-Motion Seismograph Network of Japan (K-NET, Kik-net)
398 is available at <https://www.kyoshin.bosai.go.jp/>. Preliminary event location and magnitudes used in
399 the RRSM are obtained from the EMSC (<https://www.emsc-csem.org>) bulletin via the FDSN *event*
400 web service (<http://www.seismicportal.eu/fdsnws/event/1/>); revised event metadata used in the ESM
401 are retrieved from the ISC bulletin (<http://www.isc.ac.uk/iscbulletin/>), the INGV bulletin
402 (<http://webservices.rm.ingv.it/fdsnws/event/1/>) and the GFZ bulletin ([potsdam.de/eqinfo](http://geofon.gfz-
403 potsdam.de/eqinfo)). ShakeMap is a scientific and technical framework chiefly developed and
404 maintained by the USGS (<https://github.com/usgs/shakemap>). The seismic network and station codes
405 used in this paper follow the standards of the International Federation of Digital Seismograph
406 Networks (FDSN, <http://www.fdsn.org/networks/>). One very easy option to generate proper citations
407 of seismic networks is available at <http://www.fdsn.org/networks/citation/>. The FDSN StationXML
408 format is described at <http://www.fdsn.org/xml/station/> and at
409 <https://github.com/FDSN/StationXML>. The QuakeML2.0 strong-motion package is available at
410 <https://quake.ethz.ch/quakeml/QuakeML2.0/StrongMotion>. The SEED standard is documented at
411 www.iris.edu/manuals/SEEDManual_V2.4.pdf. Details on SeisComp3 are available at
412 <https://www.seiscomp.de/seiscomp3/>. Licenses for RRSM and ESM data are consistent by the
413 Creative Commons standards (<http://creativecommons.org>). The Open Source Relational Database
414 PostgreSQL can be downloaded at <https://www.postgresql.org>. The command line tool and library
415 for transferring data with URLs (CURL) can be downloaded at <https://curl.haxx.se/>. ORCID provides

416 a persistent digital identifier (<https://orcid.org/>) for researchers. Google accounts are described at
417 <https://www.google.com/account/about/>. OpenStreetMap is a free open community-compiled map of
418 the world (<https://www.openstreetmap.org/>).

419 The websites of the funding projects are: SERA (Seismology and Earthquake Engineering Research
420 Infrastructure Alliance for Europe) <http://www.sera-eu.org/en/home/>; EPOS-IP (European Plate
421 Observing System - Implementation Phase) <https://epos-ip.org/>. The website of EFEHR is
422 <https://efehr.org/en/home/>. All the URLs mentioned in this paper were last accessed in October 2020.

423

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438

439 **References**

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547

548 *Full mailing address for each author*

549

550 giovanni.lanzano@ingv.it;

551 lucia.luzi@ingv.it;

552 carlo.cauzzi@sed.ethz.ch;

553 jarek.bienkowski@knmi.nl;

554 bindi@gfz-potsdam.de;

555 jclinton@sed.ethz.ch;

556 massimo.cocco@ingv.it;

557 maria.damico@ingv.it;

558 john.douglas@strath.ac.uk;

559 licia.faenza@ingv.it;

560 chiara.felicetta@ingv.it;

561 gallovic@karel.troja.mff.cuni.cz;

562 domenico.giardini@erdw.ethz.ch;

563 olga.ktenidou@noa.gr;

564 valentino.lauciani@ingv.it;

565 manakou@civil.auth.gr;

566 marmura@infp.ro;

567 emeline.maufroy@univ-grenoble-alpes.fr;

568 alberto.michelini@ingv.it;

569 ozener@boun.edu.tr;

570 rodolfo.puglia@ingv.it;

571 rajesh@hi.is;

572 emiliano.russo@ingv.it;

573 mshahvar@gmail.com;

574 reinoud.sleeman@knmi.nl;

575 ntheo@itsak.gr.

576

577 **Tables, with captions above each table**

578 **Table 1** – List of web services integrated in the RRSM system and examples of command-line usage.

579 Note the use of the EMSC event ID = 20161030_0000029.

<i>Product</i>	<i>Example of command line query using the web service URL, with parameters set based on the example shown in Figure 1.</i>	<i>Type of web service</i>
<i>Raw waveforms in miniSEED format</i>	<pre>curl "http://eida-federator.ethz.ch/fdsnws/datas elect/1/query?network=IV&stati on=T1213&start=2016-10- 30T06:39:18&end=2016-10- 30T06:50:18" -o waveform.mseed</pre>	<i>Standard, FDSN dataselect</i>
<i>Standardised station metadata (location, instrument response) in XML or text format</i>	<pre>curl "http://eida-federator.ethz.ch/fdsnws/station/1/que ry?network=IV&station=T1213&start=2016 -10-30T06:39:18&end=2016-10- 30T06:50:18" -o station.xml</pre>	<i>Standard, FDSN station</i>
<i>Peak-motion data in json and text format</i>	<pre>curl "www.orfeus- eu.org/odcws/rrsm/1/peak- motion?eventid=20161030_0000029" -o peakmotions.data</pre>	<i>Ad-hoc</i>
<i>Processed waveforms in mini-SEED format</i>	<pre>curl "http://www.orfeus- eu.org/odcws/rrsm/1/waveform?eventid=2 0161030_0000029" -o processed_waveforms.mseed</pre>	<i>Ad-hoc</i>

<p><i>ShakeMap _dat.xml file</i></p>	<p><code>curl "http://www.orfeus- eu.org/odcws/rrsm/1/shakemap?id=201610 30_0000029" -o shakemap_dat.xml</code></p>	<p><i>Ad-hoc</i></p>
<p><i>Response spectra in json and text format</i></p>	<p><code>curl "http://www.orfeus- eu.org/odcws/rrsm/1/peak- motion?eventid=20161030_0000029&networ k=IV&station=T1213&level=spectra" -o spectra.data</code></p>	<p><i>Ad-hoc</i></p>

580

581 **Table 2** – List of ESM WSs and example of usage using as a reference the Mw 6.5 Norcia earthquake
 582 (ESM ID EMSC-20161030_0000029).

<i>Service</i>	<i>Command line/url example</i>	<i>Action</i>
<i>Token</i>	<pre>curl -X POST -F 'message={"user_email": "user@bogus.net", "user_password": "123456789"}' "https://esm- db.eu/esmws/generate-signed- message/1/query" -o path/to/file/token.txt</pre> <p><i>Note: the command should be executed after having replaced username (user@bogus.net) and password (123456789) with the user credentials obtained upon registration.</i></p>	<i>Download token on the computer (token.txt)</i>
<i>Event</i>	<pre>curl -X POST -F "message=@token.txt" "https://esm- db.eu/fdsnws/event/1/query?eventid=EMSC- 20161030_0000029&format=text"</pre>	<i>Provide information on the event with ESM ID EMSC-20161030_0000029 according to the FDSN standard format</i>
<i>Station</i>	<pre>curl -X POST -F "message=@token.txt" "https://esm- db.eu/fdsnws/station/1/query?network=IT &station=NCR&level=channel&format=text"</pre>	<i>Provide information on the station with code NCR of the network IT according to the FDSN standard format</i>
<i>Data-download</i>	<pre>curl -X POST -F "message=@token.txt" "https://esm- db.eu/esmws/eventdata/1/query?eventid=E MSC- 20161030_0000029&catalog=ESM&processing -type=MP&data-type=ACC&format=asdf" -o outputfile.asdf</pre>	<i>Provide the corrected accelerograms of the event with ESM ID EMSC-20161030_0000029 in ASDF format (outputfile.asdf)</i>

<i>Shakemaps</i>	<code>https://esm- db.eu/esmws/shakemap/1/query?eventid=EM SC-20161030_0000029</code>	<i>Provide the input of the shakemaps of the event with ESM ID EMSC- 20161030_0000029</i>
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583

584 **List of Figure captions**

585 **Figure 1** – Synoptic picture showing the relationships and interfaces among EIDA, RRSM, ESM and
586 other data services and infrastructures within ORFEUS and EPOS. Presently there are 12 EIDA
587 nodes constituting the EIDA federated infrastructure, including the ORFEUS Data Center (ODC) in
588 the Netherlands and the Italian node at INGV. The ODC is also the main hub of all ORFEUS / EIDA
589 centralised services and products including the RRSM. The ESM is developed and maintained at
590 INGV. Both the RRSM and ESM are infrastructures promoted and coordinated by ORFEUS; while
591 they both use data and metadata from EIDA and EMSC event information, the ESM additionally
592 relies on other strong-motion networks and data sources in the greater European region, like e.g. the
593 Italian strong-motion database ITACA. The RRSM and ESM data contribute to derived products and
594 services developed within ORFEUS and EPOS. ORFEUS services are part of the portfolio of the
595 EPOS Thematic Core Service for Seismology.

596

597 **Figure 2** – RRSM event page (http://orfeus-eu.org/rrsm/event/20161030_0000029/) for the Norcia
598 (Central Italy) earthquake that occurred on October 30th 2016 at 06:40:18 UTC. There are 121 tri-
599 axial station recordings of this event in the RRSM database; the “List of Stations” in the screenshot
600 - ordered by decreasing peak ground acceleration (PGA) - shows only three of them, all pertaining
601 to the IV network (INGV, 2006). Similar pages are available for all the earthquakes included in the
602 RRSM database.

603

604 **Figure 3** – ESM usage statistics per year: a) unique visitors; b) data download.

605

606 **Figure 4** – ESM “Event” search webpage (<https://esm-db.eu/#/event/search>). The total number of
607 events until December 2020 is about 7,600.

608

609 **Figure 5** – ESM “Event” webpage of the M_w 6.5 Norcia (Central Italy) earthquake ([https://esm-](https://esm-db.eu/#/event/EMSC-20161030_0000029)
610 [db.eu/#/event/EMSC-20161030_0000029](https://esm-db.eu/#/event/EMSC-20161030_0000029)).

611

612 **Figure 6** – An example of the “Station” webpage relative to the recording station of Norcia in Central
613 Italy (network IT, station code NRC; <https://esm-db.eu/#/station/IT/NRC>). The Geotech data tab of
614 this station provides the shear-wave velocity profile of the site from in-situ geophysical investigations.

615

616 **Figure 7** – Example of the “Waveform” page for the record of the M_w 6.5 Norcia earthquake at the
617 station NRC (tab Spectra; [https://esm-db.eu/#/waveform/IT/NRC/00/EMSC-](https://esm-db.eu/#/waveform/IT/NRC/00/EMSC-20161030_0000029/HG)
618 [20161030_0000029/HG](https://esm-db.eu/#/waveform/IT/NRC/00/EMSC-20161030_0000029/HG)).

619

620 **Figure 8** – ShakeMaps representing MCS instrumentally derived intensities of the October 30, 2016,
621 $M_{6.5}$ Norcia (Central Italy) earthquake generated by using the peak-motion and event data data
622 provided by the RRSM (a) and the combined ESM+RRSM dataset (b). In panel (c), the differences
623 are calculated as (ESM+RRSM) - RRSM with the white filled triangles denoting the stations used
624 with the ESM dataset whereas the small solid black triangles indicate the RRSM dataset. The stations
625 filled with a black triangle are those present in both data sets and that have been processed manually
626 in ESM.

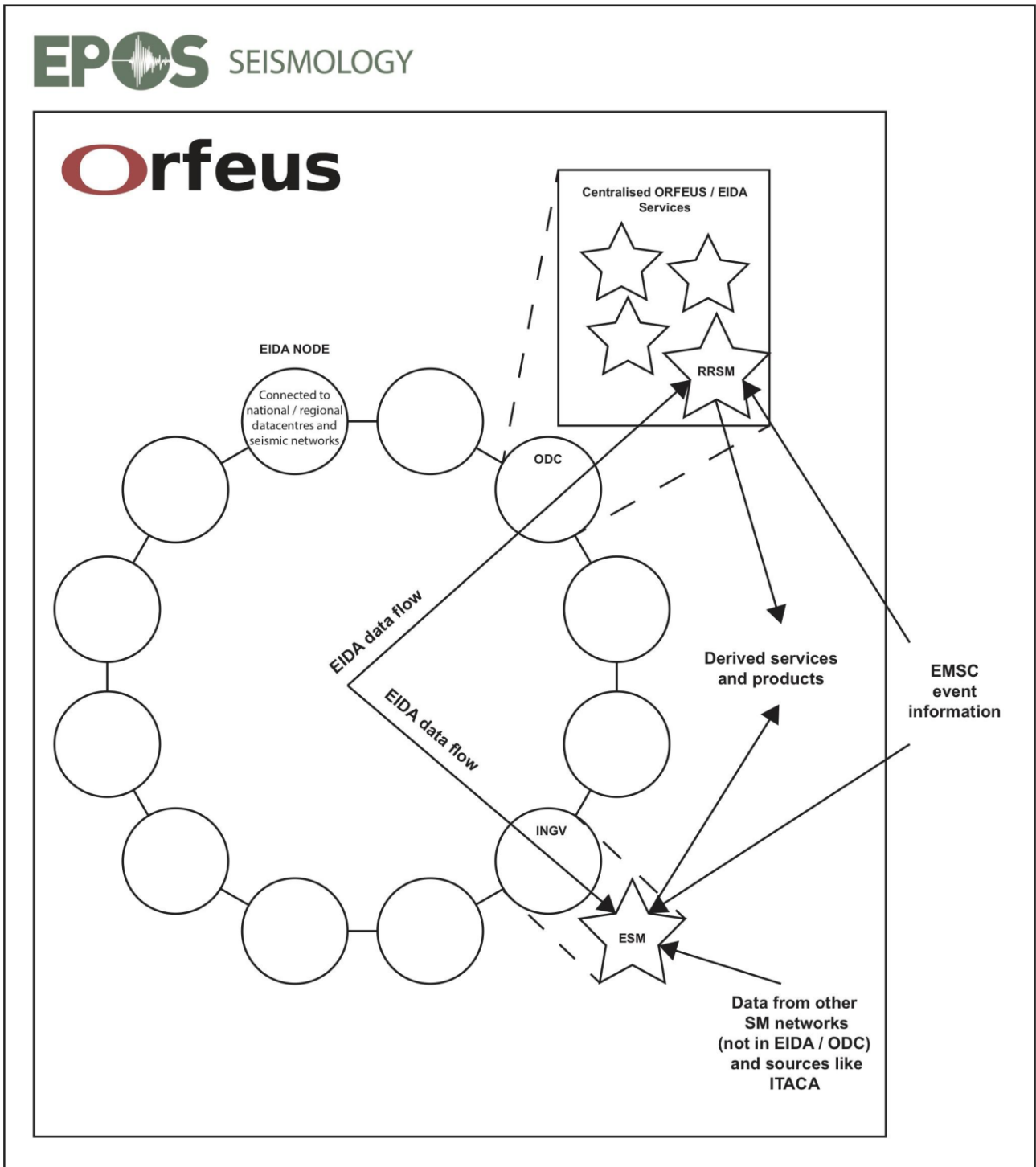
627

628 **Figure 9** – ShakeMaps representing PGA levels of the October 30, 2016, $M_{6.5}$ Norcia (Central Italy)
629 earthquake generated by using the peak-motion and event data provided by the RRSM (a) and by
630 ESM merged with RRSM (b). The differences are calculated as (ESM+RRSM) - RRSM (c). See
631 caption of Figure 8 for detail on the station symbols.

632

633

634 **Figures, with captions below each figure**



635

636 **Figure 1** – Synoptic picture showing the relationships and interfaces among EIDA, RRSM, ESM and
 637 other data services and infrastructures within ORFEUS and EPOS. Presently there are 12 EIDA
 638 nodes constituting the EIDA federated infrastructure, including the ORFEUS Data Center (ODC) in
 639 the Netherlands and the Italian node at INGV. The ODC is also the main hub of all ORFEUS / EIDA

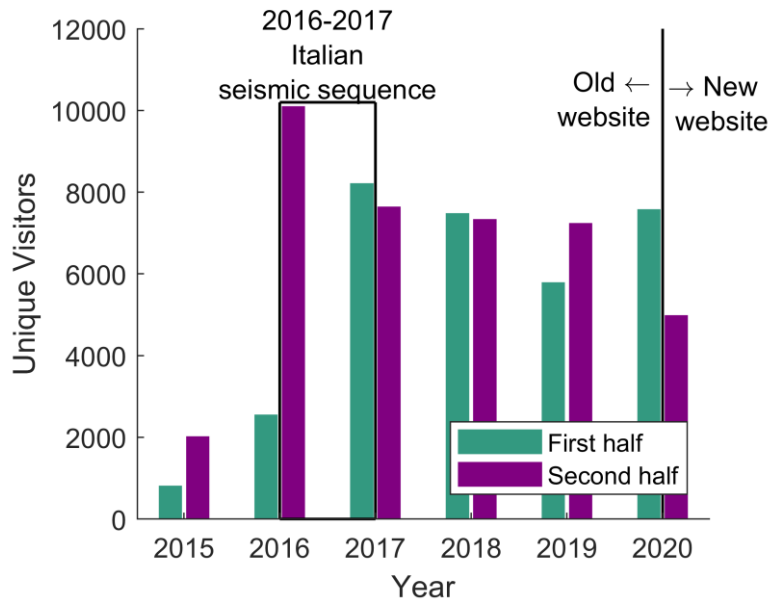
640 *centralised services and products including the RRSM. The ESM is developed and maintained at*
641 *INGV. Both the RRSM and ESM are infrastructures promoted and coordinated by ORFEUS; while*
642 *they both use data and metadata from EIDA and EMSC event information, the ESM additionally*
643 *relies on other strong-motion networks and data sources in the greater European region, like e.g. the*
644 *Italian strong-motion database ITACA. The RRSM and ESM data contribute to derived products and*
645 *services developed within ORFEUS and EPOS. ORFEUS services are part of the portfolio of the*
646 *EPOS Thematic Core Service for Seismology.*



647

648 **Figure 2** – RRSM event page (http://orfeus-eu.org/rrsm/event/20161030_0000029/) for the Norcia
 649 (Central Italy) earthquake that occurred on October 30th 2016 at 06:40:18 UTC. There are 121 tri-
 650 axial station recordings of this event in the RRSM database; the “List of Stations” in the screenshot
 651 - ordered by decreasing peak ground acceleration (PGA) - shows only three of them, all pertaining
 652 to the IV network (INGV, 2006). Similar pages are available for all the earthquakes included in the
 653 RRSM database.

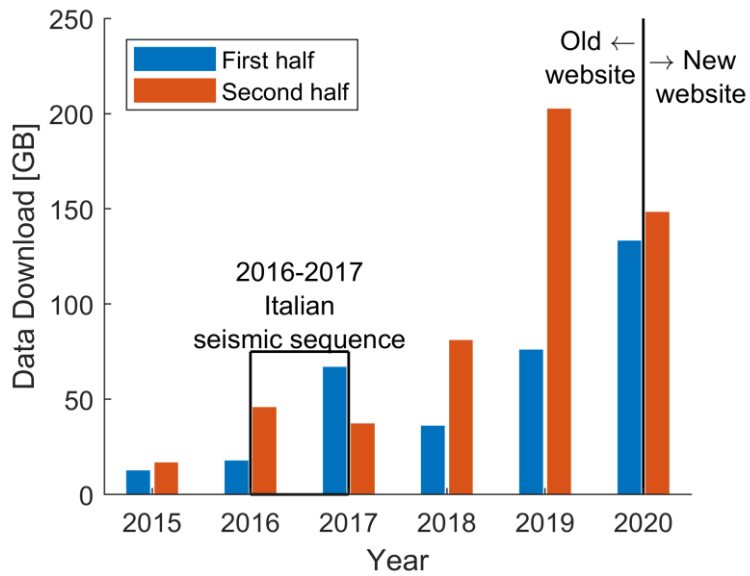
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655

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(a)



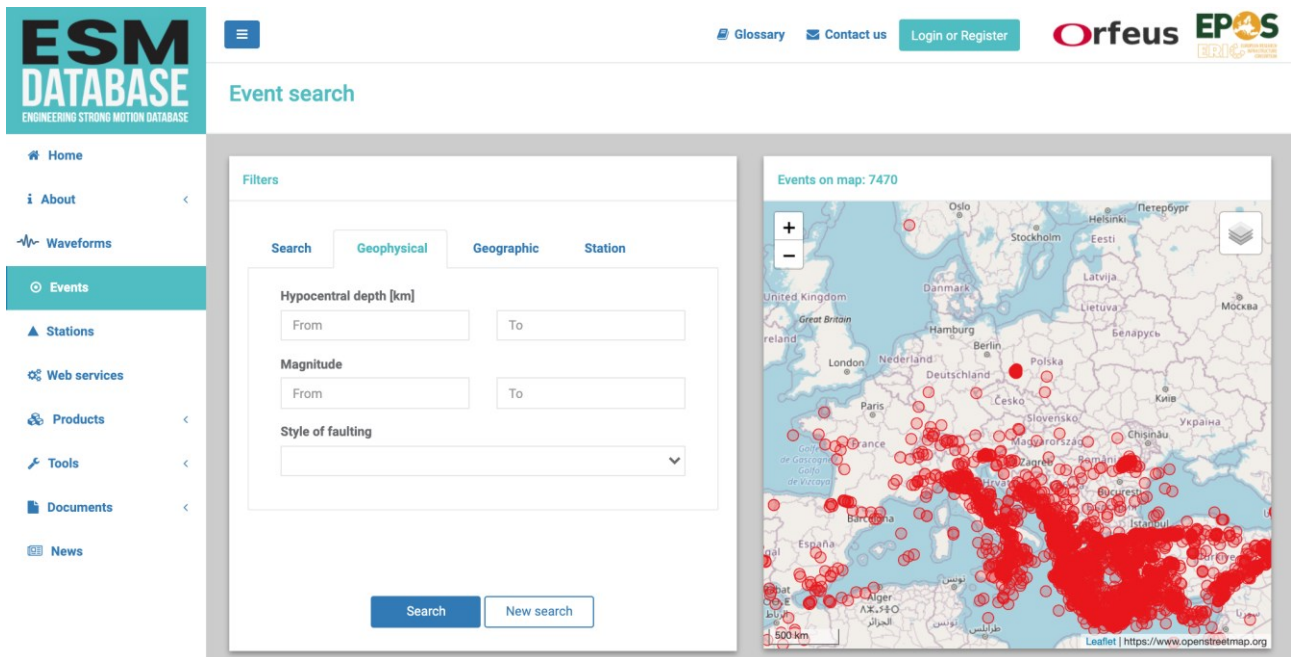
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(b)

659 **Figure 3** – ESM usage statistics per year: a) unique visitors; b) data download.

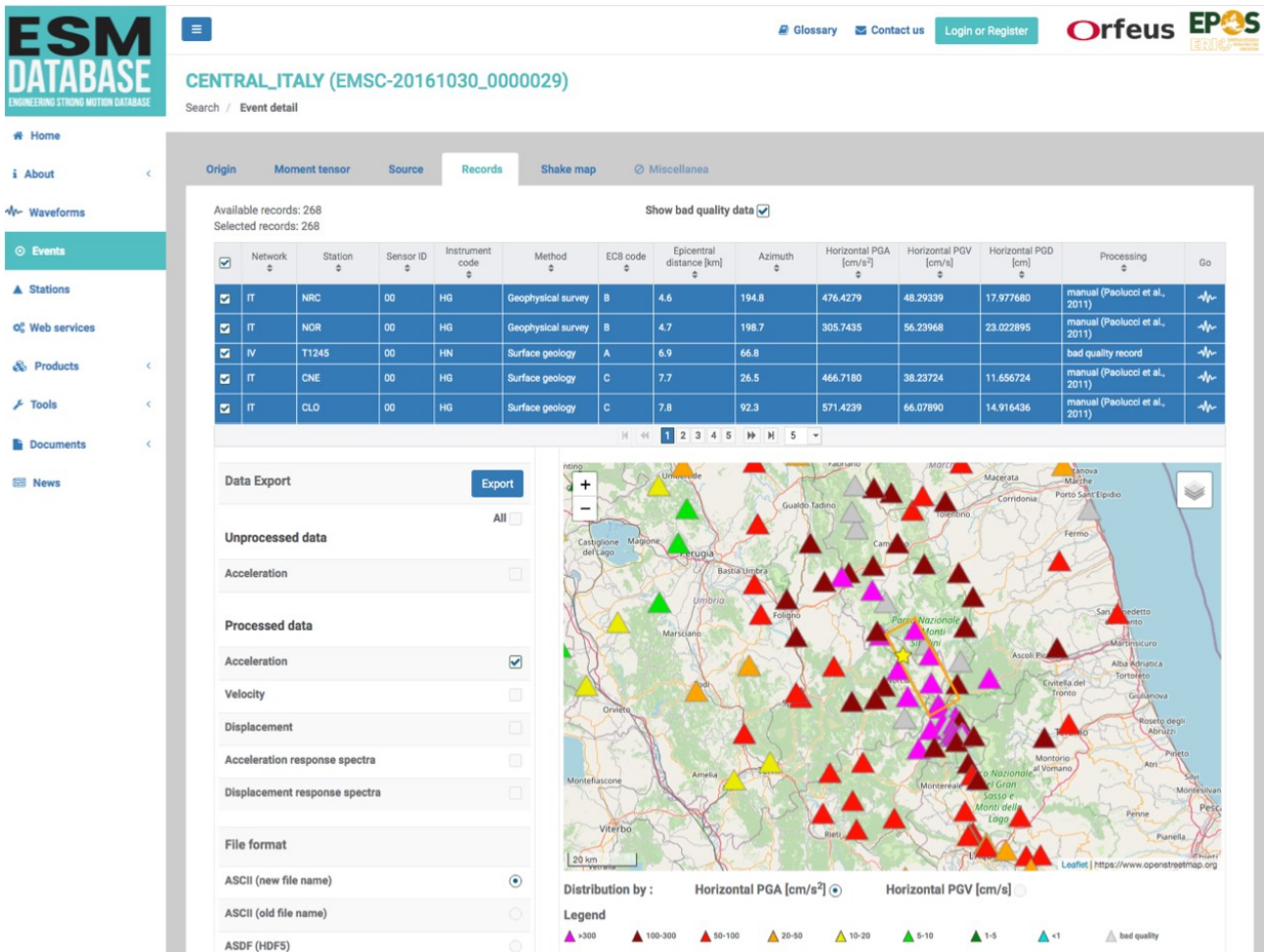
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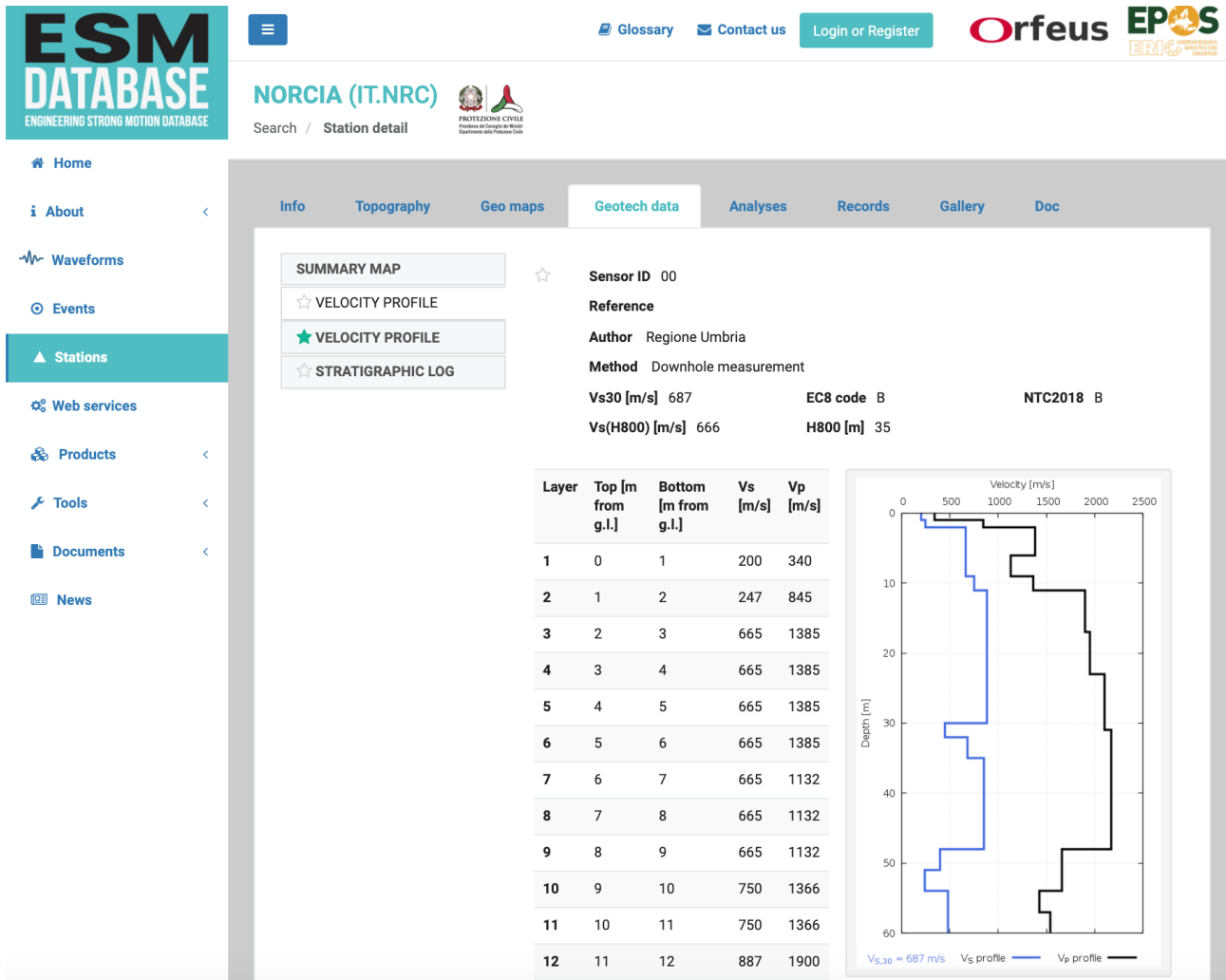
662 **Figure 4** – ESM “Event” search webpage (<https://esm-db.eu/#/event/search>). The total number of
663 events until December 2020 is about 7,600.

664



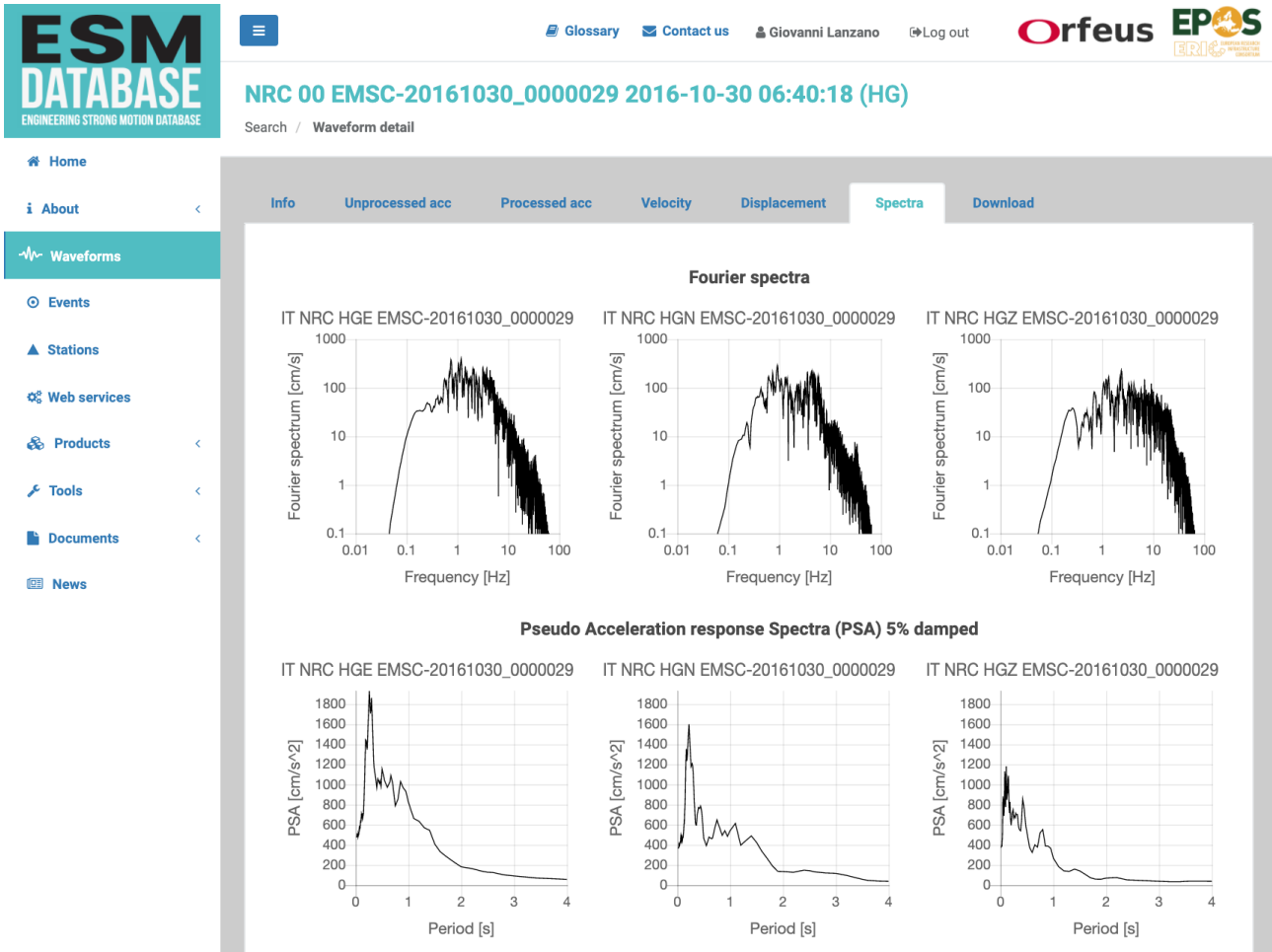
665

666 **Figure 5** – ESM “Event” webpage of the M_w 6.5 Norcia (Central Italy) earthquake (<https://esm->
667 [db.eu/#/event/EMSC-20161030_0000029](https://esm-db.eu/#/event/EMSC-20161030_0000029)).



668

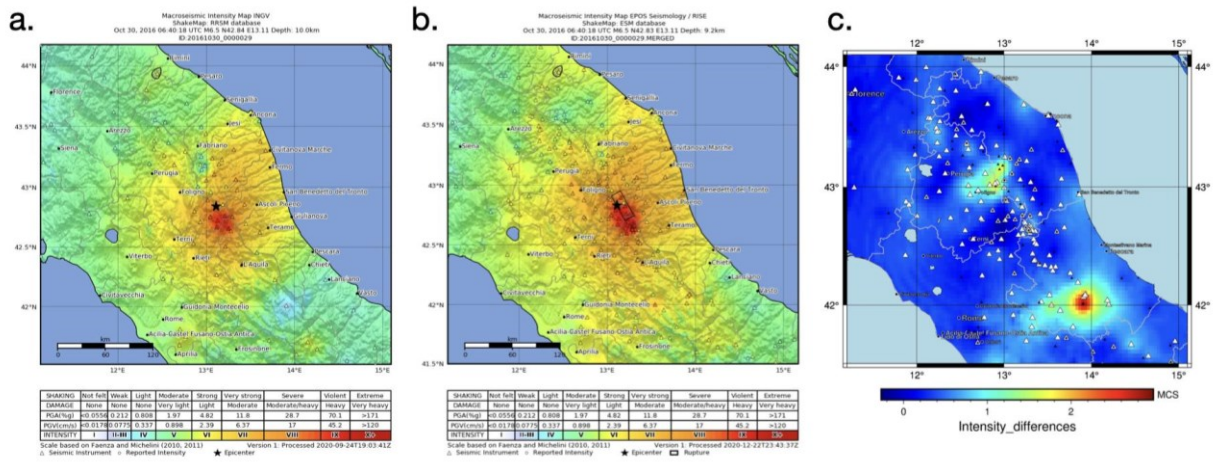
669 **Figure 6** – An example of the “Station” webpage relative to the recording station of Norcia in Central
 670 Italy (network IT, station code NRC; <https://esm-db.eu/#/station/IT/NRC>). The Geotech data tab of
 671 this station provides the shear-wave velocity profile of the site from in-situ geophysical investigations.



672

673 **Figure 7** – Example of the “Waveform” page for the record of the M_w 6.5 Norcia earthquake at the
 674 station NRC (tab Spectra; [https://esm-db.eu/#/waveform/IT/NRC/00/EMSC-](https://esm-db.eu/#/waveform/IT/NRC/00/EMSC-20161030_0000029/HG)
 675 [20161030_0000029/HG](https://esm-db.eu/#/waveform/IT/NRC/00/EMSC-20161030_0000029/HG)).

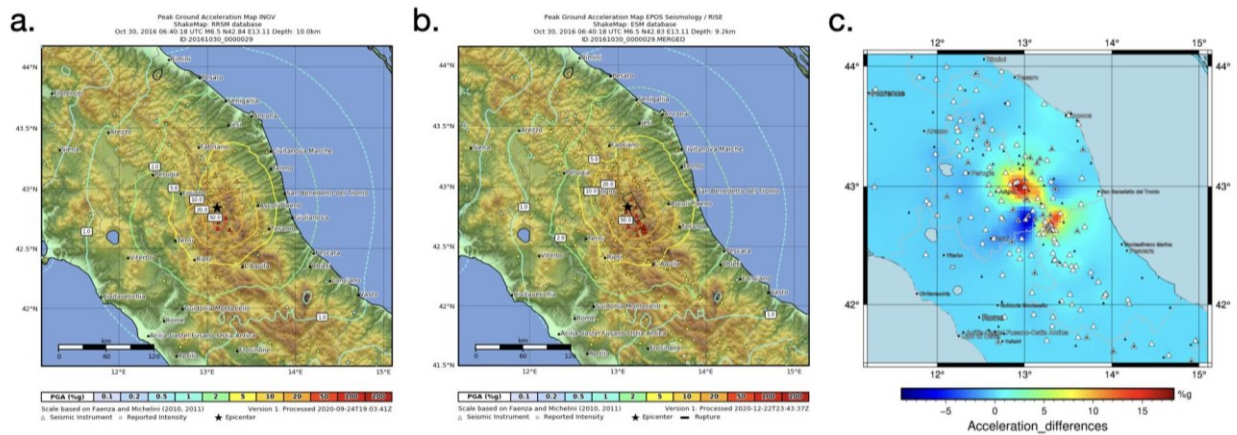
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677

678 **Figure 8** – ShakeMaps representing MCS instrumentally derived intensities of the October 30, 2016,
 679 M6.5 Norcia (Central Italy) earthquake generated by using the peak-motion and event data data
 680 provided by the RRSM (a) and the combined ESM+RRSM dataset (b). In panel (c), the differences
 681 are calculated as (ESM+RRSM) - RRSM. The white filled triangles denote the stations in the ESM
 682 dataset, i.e., with manually processed records, whereas the small solid black triangles indicate those
 683 automatically included in the RRSM dataset. Where both symbols are present, the stations have been
 684 processed by both systems.

685



686

687 **Figure 9** – ShakeMaps representing PGA levels of the October 30, 2016, M6.5 Norcia (Central Italy)
 688 earthquake generated by using the peak-motion and event data provided by the RRSM (a) and by
 689 ESM merged with RRSM (b). The differences are calculated as (ESM+RRSM) - RRSM (c). See
 690 caption of Figure 8 for detail on the station symbols.