Overview

This is the description of version 12 (V12) of the Marsquake Catalogue for InSight, which includes the Martian seismic events up to 30 June 2022 / Sol 1277 as identified by the InSight Marsquake Service (MQS). The catalogue files are available at IPGP and IRIS. New versions of the catalogue are released in sync with updated waveform data releases.

The citation for the catalogue is:


This catalogue is an update of V1-11 (InSight Marsquake Service, 2020a, b, c, d; 2021a, b, c, d; 2022a, b, c).

The catalogue is provided in two files, both in QuakeML format. One is in standard QuakeML 1.2 format, known as “basic event description” (BED). Thus, it validates against the QuakeML 1.2 schema. The second includes two Mars-specific extensions in separate XML namespaces. These include basic information for single station locations and Mars catalogue management, which is not available in the standard BED format. The additional information includes: distance, back azimuth, Mars event type, Mars event quality, and Marsquake name. The XML schema of the Mars-specific extension is provided in V4 and is unchanged since then.

A detailed description of the V3 and V9 versions of the catalogue, as well as key event presentations and MQS procedures, are provided in Clinton et al. (2021) and Ceylan et al. (2022) respectively. In general, all MQS conventions for this version, V12, are unchanged from these publications. Key details are also repeated here.

The software that has been used to compile this version (V12) is the same as released in V5. The code of the basic GUI used by MQS, developed by ETH and gempa GmbH, is available at zenodo.org (doi:10.5281/zenodo.4033316). This software provides the framework for data review, Marsquake detection, identification and quantification. The code to compute MQS distances of events, given P and S picks, is available at zenodo.org (doi:10.5281/zenodo.4302312). Updates and/or additional software critical for MQS operations, will continue to be provided in association with future catalogue releases when relevant.

An overview of the major changes between V11 and V12 (this version) is at the end of this document; detailed changelogs for each of the two catalogue files are provided separately.

MQS conventions

MQS assigns an event type and quality to each seismic event. The event type reflects the frequency content. The event quality is assigned based on the signal strength and ability to identify and interpret the phase arrivals.

MQS Event Type

<table>
<thead>
<tr>
<th>Low Frequency family: event energy generally at long period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low frequency (LF)</td>
</tr>
<tr>
<td>Broadband (BB)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High Frequency family: event energy generally at high frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Frequency (HF)</td>
</tr>
<tr>
<td>2.4Hz</td>
</tr>
<tr>
<td>Very High Frequency (VF)</td>
</tr>
</tbody>
</table>
Other Signals

| Super High Frequency (SF) | very short duration high frequency events that do not include energy at 2.4Hz or below. Typically between 5-10Hz, and horizontal energy is significantly larger than vertical energy. |

MQS Event Quality

<table>
<thead>
<tr>
<th>Label</th>
<th>Quality summary</th>
<th>Key features</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>High</td>
<td>Multiple clear and identifiable phases and clear polarisation (i.e. a reliable location is provided using well constrained distance and back-azimuth)</td>
</tr>
<tr>
<td>B</td>
<td>Medium</td>
<td>Multiple clear and identifiable phases but no or poorly constrained polarisation OR well constrained polarisation, but not enough clear phase picks for a well constrained distance estimate (i.e. location is missing or very poor)</td>
</tr>
<tr>
<td>C</td>
<td>Low</td>
<td>Signal is clearly observed but phase picking is challenging: - (HF/2.4Hz/VF) Pg and Sg pickable, but speculative OR large uncertainty OR low SNR - (LF/BB) no clear phases can be identified OR only a single phase is clearly identifiable OR multiple phases are identifiable, but no clear picks can be attributed to P and S phases - (SF) peak signal amplitude of data with 7-9 Hz BP filter above 2x10^-9 m/s</td>
</tr>
<tr>
<td>D</td>
<td>Suspicious</td>
<td>- Signal only weakly observed OR - Signal may not be attributable to a seismic event OR - (HF/2.4/VF) impossible to pick both Pg and Sg OR - (SF) peak signal amplitude of data with 7-9 Hz filter is below 2x10^-9 m/s</td>
</tr>
</tbody>
</table>

MQS Event Names

Events belonging to the Low and High Frequency families are labelled following the convention \(S[xxxx][z]\); where [xxxx] indicates the InSight mission sol the event begins on (starting from sol 0, the sol InSight landed on Mars), and [z] is a letter that ensures unique names if multiple events occur on a single Sol.

SF events are assigned the prefix letter \(T\) instead of \(S\) in order to clearly separate them from other events: \(T[xxxx][z]\).

MQS Phase Picks

Onset Phase Picks: When possible, MQS selects the first arrival times for distinct energy packets. Pick time uncertainties are on the order of seconds, if made on the waveform in the time domain; and on the order of 10's of seconds, if these are based on a distinct new signal visible on a spectrogram. Typically, only 1 or 2 energy packets are identified, if any, and are labelled P and S for LF/BB event types, and Pg and Sg for HF, VF and 2.4Hz event types. In rare cases, when arrivals at low frequency cannot be clearly attributed to P or S, they are labelled x1, x2, x3,…; and for arrivals made at high frequency (2.4Hz or higher) which cannot be clearly attributed to Pg or Sg, they are labelled y1, y2, y3. This is specifically the case for BB events that show a high frequency arrival independent of P and S.

SF events do not have phase assignments.

For each event, MQS also includes ‘picks’ for event start and end and start and end of noise windows with similar noise as observed during the event. Since there are often numerous glitches occurring within the event time window, we also include ‘clean’, glitch-free P and S coda windows when possible. Depending on the event type, the time at which peak amplitudes occur with bandpassed signals are also indicated. MQS is tracking all significant glitches within the event start and end window, but these are currently not provided in the catalogue.

Pick uncertainties are assigned for P/PP/S/SS/Pg/Sg/x?/y? but not for any other pick type.

Distances, Back Azimuth and Location

**BB/LF events:** If multiple picks are assigned as P and S phases, a distance is estimated using Martian velocity models as described in Stähler et al (2021a). If polarisation is present, the back-azimuth can be estimated primarily using the first phase arrival (assumed to be P), with the second phase arrival (assumed to be S) being used as an independent consistency check. This method is described in Zenhäusern et al. (2022), and is newly
introduced in this V12 catalogue. A single station location estimate can be made by combining the distance
and back-azimuths. This approach is based on Böse et al. (2016), and outlined in Clinton et al. (2021).
Distance / back-azimuth / location uncertainties are included in the catalogue.

HF, VF and 2.4Hz events: If multiple picks are assigned as Pg and Sg phases a preliminary distance estimate is
made using a simple crustal velocity model with \( V_p = 4 \text{ km/s}, V_p/V_s = 1.73 \). There are no back-azimuth estimates
for any of these events. Location uncertainty is provided as \( +/-(0.75 \times \text{Distance}) \) (van Driel et al., 2021).

SF events: there are currently no distance or back-azimuth estimates for these events (Dahmen et al., 2020).

Only a handful of events in the catalogue include a computed latitude/longitude location. A location is required
for a valid QuakeML origin, so by default all other events are assigned the location of the lander, at
\( \text{lat}=4.5024^\circ, \text{lon}=135.6234^\circ \).

Depth
Depths are not included in the V12 catalogue, with the exception of origins that result from moment tensor
inversions (unchanged from previous catalogues).

Magnitude
Catalogue version V12 uses magnitude relations first introduced in V7, as described in Böse et al. (2021),
replacing magnitudes in previous catalogues that were based on a pre-landing study. All events that have
catalogue distances are assigned a \( M^\text{Ma}_W \). Magnitude scales using P and S \( (m^\text{Ma}_P \text{ and } m^\text{Ma}_S) \) body phase
amplitudes, 2.4Hz resonance amplitudes \( (M^\text{Ma}_{2.4}) \), and spectral fitting \( (M^\text{Ma}_{\text{Wspec}}) \) are included, when possible. Magnitude uncertainties are included.

For the Low Frequency family BB and LF events that have both multiple origins based on S-P and ‘aligned’ (see
below) distance estimates, magnitudes are provided for each distance estimate.

Alternative Event Information

Other groups within the InSight Science team are contributing pick and location information that are being
included in the MQS catalogue. These include:

Alignments: Phase Picks, Locations, Origin Times
Giardini et al. (2020) introduce a procedure that provides aligned epicentral distances for good quality LF/BB
events that is based on similarity of waveform envelopes. Metadata includes not just the epicentral distance
but also an associated origin time as well as aligned P and S pick times. Information from this alignment
procedure has been included in the catalogue since V3. Since V7 these have been updated to include the new
LF/BB events and adopting a new background velocity model from Stähler et al. (2021a). Aligned distances
have a methodID attribute of smi:insight.mqs/algorithms/distance/aligned in their corresponding
DistanceComputation element, whereas S-P distances have a methodID attribute of
smi:insight.mqs/algorithms/distance/S-P_phases.
Since catalogue version V9 aligned distances are no longer given as the preferred distance if a pick-based
distance is available.

Secondary Phase Pick
Various groups within the InSight Science teams but independent of MQS have proposed secondary body
phase and core phase picks (Stähler et al., 2021a; Khan et al., 2021). Since different approaches are required,
these also include different P and S picks. These have been added to the V7 catalogue as additional pick
elements and are unchanged in V12. These picks are not associated to an origin through a corresponding
arrival element.

Moment Tensors
Since V7 moment tensor solutions as described in Brinkman et al. (2021) have been included for three events.
These are unchanged in V12. New in V12 are moment tensor solutions for 9 events as described in Jacob et al.
(2022), using epicenter locations from Drilleau et al. (2022). There is an overlap of two events, resulting in moment tensor information for 7 events in total in V12. The moment tensor information is contained in FocalMechanism XML elements. For all moment tensor solutions, a new origin is added to the respective event which contains the depth value from the moment tensor inversion. These origins are the only origins in the catalogue that carry depth information.

V12 Catalogue Overview

<table>
<thead>
<tr>
<th>Marsquake type events (Number in brackets is the increase since V11)</th>
<th>Total</th>
<th>A (+8)</th>
<th>B (+1)</th>
<th>C (+4)</th>
<th>D (+2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>1317</td>
<td>14 (+1)</td>
<td>173 (+4)</td>
<td>500 (+1)</td>
<td>630 (+2)</td>
</tr>
<tr>
<td>LF</td>
<td>57 (+1)</td>
<td>6</td>
<td>12 (+1)</td>
<td>20 (-1)</td>
<td>19 (+1)</td>
</tr>
<tr>
<td>BB</td>
<td>37 (+2)</td>
<td>8 (+1)</td>
<td>9 (+1)</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>HF</td>
<td>164</td>
<td>-</td>
<td>76</td>
<td>79</td>
<td>9</td>
</tr>
<tr>
<td>2.4Hz</td>
<td>989 (+3)</td>
<td>-</td>
<td>50 (+1)</td>
<td>353 (+1)</td>
<td>586 (+1)</td>
</tr>
<tr>
<td>VF</td>
<td>70 (+2)</td>
<td>-</td>
<td>26 (+1)</td>
<td>33 (+1)</td>
<td>11</td>
</tr>
<tr>
<td><strong>Super high frequency events</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1383 (+1)</td>
<td>-</td>
<td>-</td>
<td>323</td>
<td>1060 (+1)</td>
</tr>
</tbody>
</table>

Overview of Major Changes from V11 to V12

- Addition of focal mechanism/moment tensor information from Jacob et al. (2022)
- Addition of new back-azimuth PDFs from Zenhäusern et al. (2022)

25 events are now assigned back-azimuths using this method. 15 events had pre-existing back-azimuths from V11, the 14 QA events from V11, and the Q8 event S0899d. In V12, S1222a is a new QA event from the latest time window. 9 events that previously had no back-azimuth in V11 were assigned a back-azimuth in V12. These new back-azimuth values have been made preferred, which leads to new preferred epicenter locations for some events. A number of events which were not assigned a back-azimuth value in previous catalogue versions have an epicenter location for the first time in V12. Back-azimuth values computed with the original MQS method have a methodID attribute of smi:insight.mqs/algorithms/azimuth/default, whereas values from Zenhäusern et al. (2022) are denoted by a methodID attribute of smi:insight.mqs/algorithms/azimuth/10.1785/0120220019.

- Minor change to definition of Quality A and B events to reflect increased numbers of events with back-azimuths with varying quality.
- Quality upgrade of S0474a from C to B because of the availability of a new back-azimuth PDF
References


Böse, M. et al., 2021. Magnitude Scales for Marsquakes Calibrated from InSight Data, BSSA. doi.org/10.1785/0120210045


Ceylan, S. et al., 2022. The Marsquake Catalogue from InSight, Sols 0-1011. doi.org/10.1016/j.pepi.2022.106943


**InSight Marsquake Service, 2022b.** Mars Seismic Catalogue, InSight Mission; V10 2022-04-01. ETHZ, IPGP, JPL, ICL, Univ. Bristol. [https://doi.org/10.12686/a16](https://doi.org/10.12686/a16)

**InSight Marsquake Service, 2022c.** Mars Seismic Catalogue, InSight Mission; V11 2022-07-01. ETHZ, IPGP, JPL, ICL, Univ. Bristol. [https://doi.org/10.12686/a17](https://doi.org/10.12686/a17)

**Jacob, A. et al., 2022.** Seismic sources of InSight marsquakes and seismotectonic context of Elysium Planitia, Mars. Tectonophysics. doi:10.1016/j.tecto.2022.229434

**Khan, A. et al., 2021.** Upper mantle structure of Mars from InSight seismic data. Science. doi:10.1126/science.abf2966

**Kedar, S. et al., 2021.** Analyzing Low Frequency Seismic Events at Cerberus Fossae as Long Period Volcanic Quakes. [https://doi.org/10.1029/2020JE006518](https://doi.org/10.1029/2020JE006518)

**Stähler, S. et al., 2021a.** Seismic detection of the martian core. Science. doi:10.1126/science.abi7730

**Stähler, S., et al., 2021b.** Interior Models of Mars from inversion of seismic body waves (Version 1.0). IPGP Data Center. [https://doi.org/10.18715/IPGP.2021.kpmqrnz8](https://doi.org/10.18715/IPGP.2021.kpmqrnz8)

**Zenhäusern, G. et al., 2022.** Low-Frequency Marsquakes and Where to Find Them: Back Azimuth Determination Using a Polarization Analysis Approach. BSSA. [https://doi.org/10.1785/0120220019](https://doi.org/10.1785/0120220019)