Mars Seismic Catalogue, InSight Mission; V14 2023-04-01

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Overview

This is the description of version 14 (V14) of the Marsquake Catalogue for InSight, which includes the Martian seismic events up to 31 December 2022 (Sol 1456) as identified by the InSight Marsquake Service (MQS). The last seismic waveform data downlinked from the lander is for 13 December 2022 (Sol 1439), and the last event was recorded on 19 November 2022 (Sol 1415). The catalogue files are available at IPGP and IRIS. This is the last version of the catalogue to be released in sync with updated waveform data releases.

The citation for the catalogue is:

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This catalogue is an update of V1-13 (***InSight Marsquake Service, 2020a, b, c, d; 2021a, b, c, d; 2022a, b, c, d; 2023a***).

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, V14, are unchanged from the V9 publication. Key details are also repeated here.

The software that has been used to compile this version (V14) 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).

An overview of the major changes between V13 and V14 (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

Low Frequency family: event energy generally at long period	
Low frequency (LF)	energy in 3 components all below 2.4 Hz.
Broadband (BB)	energy in 3 components predominantly below 2.4 Hz though also includes excitement at and possibly above 2.4 Hz.
High Frequency family: event energy generally at high frequency	
High Frequency (HF)	energy in 3 components predominantly at 2.4 Hz and above. 'Predominantly' indicates some energy below 2.4 Hz is possible.
2.4Hz	energy in 3 components centered around 2.4 Hz resonance, with very limited excitation above or below. (It is likely these are small amplitude HF events.)
Very High Frequency (VF)	special case of high frequency events that show clear differences in energy between vertical and horizontal components. Horizontal energy is significantly larger than vertical energy at higher

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

MQS Event Quality

Label	Quality summary	Key features
A	High	Multiple clear and identifiable phases and clear polarisation (i.e. a reliable location is provided using well constrained distance and back-azimuth)
B	Medium	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)
C	Low	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
D	Suspicious	- Signal only weakly observed OR - Signal may not be attributable to a seismic event OR - (HF/2.4Hz/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

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 (2.4 Hz 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.

There are a handful of LF family events with additional phases identified:
S1000a and S1094b are distant events beyond the core shadow, and body phases are labelled as PP and SS. S1000a includes a weak precursor to the PP that has been identified as Pdiff ***(Horleston et al., 2022***).
S1222a is the largest event in the V14 catalogue, and includes observations of fundamental and 1st overtone Love and Rayleigh waves that are made at different frequency bands ***(Kawamura et al., 2022)***.

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/Pdiff/x?/y? and surface waves, 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 polarization 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 has been included since the V12 catalogue. Origins with back-azimuth values from this method are the preferred origins and carry a methodID element of *smi:insight.mqs/algorithms/azimuth/10.1785/0120220019*. Events with a back-azimuth from the standard MQS processing as contained in catalogue V11 are listed with an additional origin since V13. This origin combines the V11 back-azimuth with the current, V14 MQS preferred distance. These origins are not preferred and can be identified through the methodID element *smi:insight.mqs/algorithms/azimuth/default*. For these origins, no magnitudes are listed in the catalogue, since the magnitudes are the same as the ones from the same-distance preferred origin using the BAZ from ***Zenhäusern et al. (2022).***

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 Vp=4 km/s, Vp/Vs=1.73. There are no back-azimuth estimates for any of these events. Location uncertainty is provided as +/-(0.75xDistance) (***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 lat=4.5024°, lon=135.6234°.

Depth

Depths are not included in the origin elements of the V14 catalogue, with the exception of

- origins that result from moment tensor inversions (unchanged from previous catalogues)
- origins that are from confirmed impacts (new since catalogue version V13)

Magnitude

Catalogue version V14 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_W^{Ma}. Magnitude scales using P and S (m_b^{Ma} and m_{bS}^{Ma}) body phase amplitudes, 2.4 Hz resonance amplitudes ($M_{2.4Hz}^{Ma}$), and spectral fitting (M_{Wspec}^{Ma}) are included, when possible. Magnitude uncertainties are included.

For the Low Frequency family BB and LF events that have multiple origins based on S-P and 'aligned' (see below) distance estimates, or known impact locations, magnitudes are provided for each origin using the calculated distance.

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:

Impact locations from orbital imaging

Eight seismic event locations from the MQS catalogue could be identified with impact locations found in images from the Context Camera (CTX) on the Mars Reconnaissance Orbiter (MRO). The events S0553a, S0793a, S0981c, S0986c ***(Garcia et al., 2022)***, and S1000a, S1094b ***(Posiolova et al., 2022)*** were first labelled as impacts in V13 and are unchanged in V14. S1034a and S1160a ***(Daubar et al., 2023)*** are new in this version, V14. For these events, an additional origin element with the impact location has been added. The QuakeML basic event description event type has been changed from ‘other’ to ‘meteorite’. The Mars event type remains as originally assigned by MQS – VF for the near-Insight events in ***Garcia et al. (2022) and Daubar et al. (2023)***; and BB for the distant impacts described in ***Posiolova et al. (2022)***.

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 provided 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 V14. 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. In V12 moment tensor solutions for 9 events have been added as described in ***Jacob et al. (2022),*** using epicenter locations from ***Drilleau et al. (2022)***. These are unchanged in V14. 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 and origins from confirmed impacts are the only origins that carry depth information.

V14 Catalogue Overview

Marsquake type events (Number in brackets is the increase since V13)

	Total	A	B	C	D
Total	1323 (+5)	14	175 (+1)	501 (+1)	633 (+3)
LF	59 (+2)	6	12	20	21 (+2)
BB	39 (+2)	8	10 (+1)	15	6 (+1)
HF	162 (-2)	-	74 (-2)	79	9
2.4Hz	989	-	50	353	586
VF	74 (+3)	-	29 (+2)	34 (+1)	11

Super high frequency events

	Total	A	B	C	D
SF	1392 (+9)	-	-	325 (+2)	1067 (+7)

Overview of Major Changes from V13 to V14

- No new properties or structural change in catalogue organization.
- There is one new event S1415a (BB/QB) in the time period since the end of V13 (30 September 2022).
- Event review prompted by extended Machine Learning-informed catalogues ***(Dahmen et al., 2022; Stott et al., 2023)*** and comodulation analysis ***(Charalambous et al., 2021)*** led to the addition of four additional events in periods covered by earlier catalogues. These are S0943h (LF/QD), S0934c (BB/QD), S0774a (VF/QC), and S0345e (LF/QD).
- Quality control review led to re-classification of a number of events: S0490a (VF/QB) and S1135c (VF/QB) were changed from Mars event type HF to VF.
- Events S1034a and S1160a have been classified as impact events ***(Daubar et al., 2023)***.
- In version V13 and previous version of the catalogue, the QuakeML catalogue file conforming to the QuakeML 1.2 standard does not contain the *preferredMagnitudeID* XML child element of the *event* element for some events. This omission does not occur in the full QuakeML file containing non-standard Mars extensions. The *preferredMagnitudeID* element contains a reference to the preferred magnitude value for the event in correspondence to the preferred origin, referred to by the *preferredOriginID* element. The *preferredOriginID* element is listed for all events. In catalogue version V14, all events with magnitude(s) in the QuakeML 1.2 version of the catalogue file have a *preferredMagnitudeID* element.

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