Mars Seismic Catalogue, InSight Mission; V12 2022-10-01

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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:
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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

Low Frequency family: event energy generally at long period	
Low frequency (LF)	energy in 3 components all below 2.4Hz.
Broadband (BB)	energy in 3 components predominantly below 2.4Hz though also includes excitement at and possibly above 2.4Hz.
High Frequency family: event energy generally at high frequency	
High Frequency (HF)	energy in 3 components predominantly at 2.4Hz and above. 'Predominantly' indicates some energy below 2.4Hz is possible.
2.4Hz	energy in 3 components centered around 2.4Hz 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 2.4Hz or below. Typically between 5-10Hz, 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/2.4/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

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

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_W^{Ma}. Magnitude scales using P and S (m_b^{Ma} and m_{bS}^{Ma}) body phase amplitudes, 2.4Hz resonance amplitudes ($M_{2.4\,Hz}^{Ma}$), 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 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 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 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

Marsquake type events (Number in brackets is the increase since V11)

	Total	A	B	C	D
Total	1317 (+8)	14 (+1)	173 (+4)	500 (+1)	630 (+2)
LF	57 (+1)	6	12 (+1)	20 (-1)	19 (+1)
BB	37 (+2)	8 (+1)	9 (+1)	15	5
HF	164	-	76	79	9
2.4Hz	989 (+3)	-	50 (+1)	353 (+1)	586 (+1)
VF	70 (+2)	-	26 (+1)	33 (+1)	11

Super high frequency events

	Total	A	B	C	D
SF	1383 (+1)	-	-	323	1060 (+1)

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 QB 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., 2016. A Probabilistic Framework for Single-Station Location of Seismicity on Earth and Mars. PEPI. doi.org/10.1016/j.pepi.2016.11.003

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

Brinkman, N. et al., 2021. First Focal Mechanisms of Marsquakes, JGR Planets. doi.org/10.1029/2020JE006546

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

Clinton, J. et al., 2021. The Marsquake Catalogue from InSight, Sols 0-478. doi.org/10.1016/j.pepi.2020.106595

Dahmen, N. et al., 2020. Super high frequency events: a new class of events recorded by the InSight seismometers on Mars. JGR Planets. doi.org/10.1029/2020JE006599

van Driel, M. et al., 2021. High frequency seismic events on Mars observed by Insight. JGR Planets. https://doi.org/10.1029/2020JE006670

Drilleau, M. et al., 2022. Marsquake Locations and 1-D Seismic Models for Mars From InSight Data. JGR Planets. doi:10.1029/2021JE007067

Giardini, D. et al., 2020. The seismicity of Mars, Nature Geoscience. doi:10.1038/s41561-020-0539-8

InSight Marsquake Service, 2020a. Mars Seismic Catalogue, InSight Mission; V1 2/1/2020. ETHZ, IPGP, JPL, ICL, ISAE-Supaero, MPS, Univ. Bristol. https://doi.org/10.12686/a6

InSight Marsquake Service, 2020b. Mars Seismic Catalogue, InSight Mission; V2 2020-04-01. ETHZ, IPGP, JPL, ICL, ISAE-Supaero, MPS, Univ. Bristol. https://doi.org/10.12686/a7

InSight Marsquake Service, 2020c. Mars Seismic Catalogue, InSight Mission; V3 2020-07-01. ETHZ, IPGP, JPL, ICL, ISAE-Supaero, MPS, Univ. Bristol. https://doi.org/10.12686/a8

InSight Marsquake Service, 2020d. Mars Seismic Catalogue, InSight Mission; V4 2020-10-01. ETHZ, IPGP, JPL, ICL, MPS, Univ. Bristol. https://doi.org/10.12686/a9

InSight Marsquake Service, 2021a. Mars Seismic Catalogue, InSight Mission; V5 2020-01-04. ETHZ, IPGP, JPL, ICL, MPS, Univ. Bristol. https://doi.org/10.12686/a10

InSight Marsquake Service, 2021b. Mars Seismic Catalogue, InSight Mission; V6 2021-04-01. ETHZ, IPGP, JPL, ICL, MPS, Univ. Bristol. https://doi.org/10.12686/a11

InSight Marsquake Service, 2021c. Mars Seismic Catalogue, InSight Mission; V7 2021-07-01. ETHZ, IPGP, JPL, ICL, Univ. Bristol. https://doi.org/10.12686/a12

InSight Marsquake Service, 2021d. Mars Seismic Catalogue, InSight Mission; V8 2021-10-01. ETHZ, IPGP, JPL, ICL, Univ. Bristol. https://doi.org/10.12686/a13

InSight Marsquake Service, 2022a. Mars Seismic Catalogue, InSight Mission; V9 2022-01-01. ETHZ, IPGP, JPL, ICL, Univ. Bristol. https://doi.org/10.12686/a14

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

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

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

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

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