ONE MARTIAN YEAR OF SEISMIC MONITORING OF MARS BY INSIGHT: SEIS RESULTS AND PERSPECTIVES FOR THE EXTENDED MISSION.

P.Lognonné[1], W. B. Banerdt[2], D.Giardini[3], M. P. Panning[2], W.T.Pike[4], D.Antonangeli[5], J.Ballestra[6], D.Banfield[7], C. Beghein[8], E.Beucler[9], N. Bowles[10], E. Bozdag[11], S. Ceylan[3], C.Charalambous[4], U. Christensen[12], J. Clinton[4], N.Compaire[13], G. Collins[10], N.Dahmen[3], I.Daubar[14], M.van Driel[3], M.Drilleau[13], B.Fernando[10], M.Froment[1], R. Garcia[13], J. Irving[15], A.Khan[3], T. Kawamura[1], S. Kedar[2], B.Kenda[1], B. Knapmeyer-Endrun[16], R. Lorenz[17], L. Margerin[18], L.Martire[13], C. Michaut[19], D. Mimoun[13], N.Murdoch[13], F. Nimmo[20], C.Perrin[9], A-C Plesa[21], N. Schmerr[22], J.R.Scholz[12], S.Smrekar[2], D.Sollberger[3], A. Spiga[23], S.Stähler[3], E.Stutzmann[1], N. Teanby[15], J. Tromp[23], R. Weber[24], M. Wieczorek[6], N. Wójcicka[4], H.Xu[8], C.Agard[25], E.Barrett[2], J.L.Berenguer[6], M.Böse[3], V.Conejero[1], A.Horleston[15],K.Hurst[2],C.Ferrier[25],N.Fuji[1],T.Gabsi[1], E.Gaudin[26], B.Jaillant[26] A.Jullien[25], F.Karakostas[22], P.Labrot[1], F.Meunier[25], C.Pardo[1], J.ten Pierick[3], M.Plasman[1], L.Rochas[25], A.Sauron[3],G.Sainton[1], Z.Xu[1], C.Yana[25] and the InSight/SEIS Science Team; [1]Université de Paris-Institut de physique du globe de Paris-CNRS (lognonne@ipgp.fr), [2]Jet Propulsion Laboratory, California Institute of Technology, [3]ETH-Zürich, [4]Imperial College, [5]IMPMC-Sorbonne Université, [6]Obs. Côte d'Azur, [7]Cornell, [8]UCLA, [9]LPG Nantes,[10]Oxford, [11]CO School of Mines, [12]MPS, [13]ISAE-SUPAERO, [14]Brown University,[15]Bristol University, [16]Univ. Cologne, [17]JHU-APL, [18]IRAP-Univ. Toulouse, [19]ENS Lyon, [20]UCSC, [21]DLR-Berlin, [22]UMD, [23]LMD-Sorbonne Université, [23]Princeton, [24]MSFC,[25]CNES, [26]Telespazio

Introduction: The InSight mission landed on Mars on November, 26, 2018 [1]. The Seismic Experiment for Interior Structure (SEIS) [2] started continuous monitoring with VBBS on February, 14th, 2019. A full Martian year of monitoring was therefore achieved on January, 1st, 2021, with 97% of time coverage, due mostly to an interruption during conjunction. We present here the scientific results of this first Martian year, in term of seismic noise, seismicity and determination of Mars interior structure and conclude by perspective for the extended mission.

Seismic noise: While the seismic noise monitored on the InSight lander prior the deployment of the SEIS experiment on the ground was as much, if not more, wind-sensitive than Viking [3], SEIS has been able, after its successful deployment on the ground, to record both extremely low noise during the quietest time, with level never experienced by a seismic sensor even on the Moon [4] and down to close from 10^{-10} $m/s^2/Hz^{1/2}$ in acceleration spectral amplitude at a few seconds of period (although the sensor is still wind sensitive during the atmospheric active part of the day [5]). Since sol 500, the low noise time window has been lost due to the stronger atmospheric activity, but is expected to come back in about 100 sols (Figure 1). The seismic noise has a complex structure, with large linearly polarized contributions related to the ground deformation induced by the wind forces acting on the lander [6,7], thermal ground deformation related to temperature fluctuation [8] and thermal glitches related the un-perfect coupling of the SEIS instrument on the ground and instrument relaxations[9]. Part of these glitches are not random in time, as related to temperature while other are correlated to pressure drops[10]. These non-seismic noises must be handled with care as they may affect autocorrelation analysis[10,11]. The noise has a significant polarization, possibly related to acoustic emission from wind flows[12]. Although proposed in some early work[13], more analysis are necessary for a clear identification of a possible background noise associated to seismic waves[12].

Seismic activity: By January 1st, 2021, 1286 events have been reported by the MarsQuake Service[14] and have been classified in term of event frequency (with 30, 14, 362, 55, 30, 790 respectively Low frequency, broadband, 2.4 Hz, High Frequency (HF), Very HF, super HF and strange, see Figure 1 for their occurrence timing).

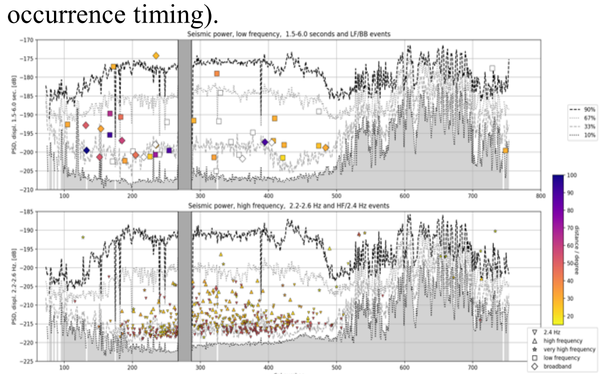

Figure 1. Amplitude of SEIS VBB noise and occurrence of events until January 1st. Units are db with respect to 1 $m/s/Hz^{1/2}$ at long period (above) and short period (below).

The seismic activity of Mars is found to be intermediate between Moon and intraplate Earth [1], and a cluster of seismicity has been located near Cerberus Fossae [15], at an epicentral distance of 26-27° and with magnitude 3.5-4 events having a source mechanism coherent with the fault systems[16]. No event with magnitude larger than 4 has been detected so far, which suggest a frequency-magnitude law different from Earth, possibly related to the very low strain rate of Mars tectonics. Most of the 2.4 Hz and High and Very High events are from epicentral distance in the range of 20-30° (1200-1800km) and with low magnitude (<2) [17]. Most of the MQS reported events are Super High Frequency events, which are proposed to be analog to the Moon thermal quakes [18]. No impact has been yet identified on the seismic data [19]. This lack of impact signal might be associated to the small size of the CTX reported impacts and/or to low seismic efficiency for these low size impacts [20,21].

Meteorological events: SEIS has also detected atmospheric events, through the coupling of the low rigidity surface with the atmosphere. Most of them are associated to pressure drops [23] and turbulence of the boundary layer [24] and are the primary reasons for the large seismic noise detected during the day [1,4,25,26, 27]. A few of the reported LF events from MQS have been proposed as infrasound events [28].

Subsurface and upper crust structure: The subsurface has been constrained by both the recording of the HP3 hammering [4,29] and the joint SEIS-APSS inversion of the pressure-drop events [1,4,25,27].The upper crust has been constrained through receiver function analysis [4] and is characterized by low seismic velocities, likely associated to both an high porosity and significant alteration, possibly related to water circulation in Mars ancient time or low-seismic material[30].

Deeper structure: The spectrum of the recorded events has been able to provide first constrains on scattering and attenuation of Mars and to compare them to the Earth and Moon [4,15]. The most recent analysis have focused on both Receiver function and auto-correlation for the crust [31], multiply reflected body waves for the upper mantle [32] and core reflected phase for the Core Mantle Boundary [33] and start to reveal the deep structure of Mars.

Perspectives for the extended mission: One of the most important goal of the extended mission will be to reduce with different strategies the background non-seismic noise recorded by SEIS. This will be made by better understanding, and therefore modeling of the lander noise, by pressure decorrelation [34] thanks to APSS data [35] but also by covering the tether with regolith materials using the scoop of the robotic arm. We can expect these efforts to improve SNR, allow the detection of more long period seismic signals, including possibly surface waves [36,37] and even possibly signals associated to the atmospheric entry and landing of future mars missions [38]. The later remains nevertheless a challenge, even if already illustrated by Netflix movies[39].

Education and Data access: SEIS data have been distributed to about 100 middle and high schools in 15 countries, allowing students to discover this new field of seismology [40] and InSight@home activities have been furthermore proposed to kids during the COVID confinement [41]. All SEIS data and MQS activity catalogues until October, 14th, 2020, are available at the SEIS website (http://seis-insight.eu) as well as IRIS and NASA-PDS depository. An access to most of the reference cited in this abstract can also be found in the SEIS website.

Acknowledgments: The SEIS team acknowledges the supports of NASA, CNES, ANR, UKSA SSO and DLR for the experiment funding and of the InSight operation team for delivering SEIS data and operating the InSight mission.

References: [1] Banerdt *et al.* (2020), Nature Geoscience, 13, 183-189. [2] Lognonné *et al.* (2019) , Space Sci Rev, 215, 12 [3] Panning *et al.* (2020). JGR: Planets, 125, e2019JE006353 [4] Lognonné *et al.* (2020) Nature geoscience, 13, 213-220 [5] Ceylan *et al.* (2020), Physic. Planet. Earth. Int, in press. [6] Murdoch *et al. (2017)*, Space Science Review, 211, 429-455 [7] Charalambou et al (2021), submitted to Earth Space Science [8] Stähler *et al*.(2020) GRL, 47, e2020GL089099 [9] Scholz *et al* (2020) Earth and Space Science, 7, e2020EA001317 [10] Deng & Levander (2020), GRL, 47, e2020GL089630 [11] Compaire, *et al.* (2020), submitted to JGR. [12] Stutzmann *et al.* (2021) JGR: Planets, 126, e2020JE006545 [13] Suemoto *et al.* (2020) GRL, 47, e2020GL087123.[14] Clinton *et al.* (2020), Physic. Planet. Earth. Int., 106595 [15] Giardini *et al.* (2020), Nature Geoscience, 13, 205-212 [16] Brinkman *et al.* (2021). submitted to JGR-Planets [17] van Driel *et al.* (2020), JGR: Planets, in press. [18] Dahmen *et al.* (2020) JGR: Planets, e2020JE006599 [19] Daubar *et al.* (2020). JGR: Planets, 125, e2020JE006382. [20] Froment *et al.* (2020) GRL, 47, e2020GL087393. [21] Wójcicka *et al.* (2021) JGR: Planets, 125, e2020JE006540. [23] Perrin *et al.* (2020) GRL, 47, e2020GL087234 [24] Spiga *et al.* (2020), JGR : Planets, in press [25] Kenda *et al. (2020)* JGR: Planets 125, e2020JE006387 [26] Lorenz *et al.* (2021), Icarus, 355 [27] Murdoch et al. (2021), submitted to JGR: Planets. [28] Martire *et al.* (2020) JGR: Planets, 125, e2020JE006376. [29] Sollberger *et al.* (2021), Submitted to Earth and Space Science [30] Pan *et al.* (2020), Icarus, 338 [31] Panning *et al.*, LPSC2021 Abstract [32] Khan *et al.* LPSC2021 Abstract [33] Stähler *et al.* LPSC 2021 Abstract. [34] Garcia *et al.*(2020) JGR: Planets, 125, e2019JE006278 [35] Banfield *et al.* (2020), Nature Geoscience, 13,190-198 [36] Drilleau *et al*. (2020), Earth and Space Science, 7, e2020EA001118. [37] Xu et al. (2020), Earth and Space Science, 7, e2020EA001263 [38] Fernando *et al.* (2021), submitted to Earth and Space Science [39] Away, episode 8, Netflix (2020) [40 Balestra *et al.* (2020), Seismological Research Letters, 91, 1064–1073 [41] https://insight.oca.eu/fr/insight-home