A CERBERUS FOSSAE SEISMIC NETWORK S. C. Stähler[1], M. P. Panning[2], D. Antonangeli[3], W. B. Banerdt[2], D. Banfield[4], M. Banks[5], S. Ceylan[1], C. Charalambous[6], J. Clinton[1], I. Daubar[7], B. Fernando[8], D. Giardini[1], M. Grott[9], A. Horleston[10], K. Hurst[2], T. Kawamura[11], A. Khan[1], D. Kim[1], M. Knapmeyer[9], B. Knapmeyer-Endrun[12], R. Lorenz[13], L. Margerin[14], A. Marusiak[2], S. Menina[14], A. Mittelholz[1], N. Murdoch[15], Y. Nishikawa[16], C. Perrin[17], W. T. Pike[6], C. Schmelzbach[1], N. Schmerr[18], M. Schimmel[18], A. Spiga[3], A. Stott[15], J. Taylor[9], and R. Weber[19]. [1]ETH Zürich, Switzerland (simon.staehler@erdw.ethz), [2]JPL, Pasadena CA, USA [3]Sorbonne U, Paris, France [4]Cornell, Ithaka NY, USA [5]NASA GSFC, Greenbelt MD, USA, [6]Imperial College, London, UK, [7]Brown U, Providence RI, USA [8]U Oxford, UK [9]DLR, Berlin, Germany, [10]U Bristol, UK [11]IPGP, Paris, France [12]U Cologne, Germany, [13]APL, JHU, USA, [14]U Toulouse, France, [15]ISAE-Supaero, Toulouse, France, [16]KUT, Kochi, Japan, [17]LPG, Nantes, France [18]U Maryland, College Park MD, USA and [19]NASA MSFC, Huntsville AL, USA

Scientific Rationale: For hundreds of years, planet Mars has been the subject of heated controversy amongst scientists. Specifically the question whether the planet might have been less arid and cold and more habitable in the past has been discussed over and over again. It is by now widely accepted that the planet had a wet and periodically warm past in the Noachian [1], but it is still open whether liquid water has played any role geologically in recent times or is even present in significant amounts near the surface today [2]. One key area are the Cerberus Fossae, a system of $<$ 10 Ma old, 1200 km long grabens in Eastern Elysium Planitia. They connect to sediments in Athabasca Valles that have been interpreted as being created by volcanic activity that melted a significant cryospheric layer leading to catastrophic flooding 8-10 Ma ago [3], but could alternatively be explained by very low viscosity lava as well [4, 5].

The InSight mission [6] deployed the first successful seismometer to the surface of Mars and could detect a significant number of marsquakes over three years. The most significant quakes of the first year on Mars have been located specifically in the Cerberus Fossae system [7, 8], with focal mechanisms of an extensional tectonic setting [9]. Of the remaining 40 deep (LF) quakes, a significant number is located in a distance compatible with a source in or near Cerberus Fossae as well [10]. This means that at least on the hemisphere of InSight, tectonic activity is not primarily driven by cooling and contraction of the planet (as proposed by [11, 12], among others), but by highly localized stress, potentially related to ongoing volcanic activity [13]. A second type of shallow marsquakes shows an upper crust that combines strong heterogeneities and low seismic attenuation, reminiscent of lunar quakes [14, 15], at least in the upper kilometers. These observations seem incompatible with large amounts of water in the crust, either as a frozen groundwater layer or as water saved within minerals (which has been proposed as the sink of the water lost since the Noachian [16]). In combination, InSight has therefore shown that even the first analysis of seismic data challenges the concept of dominant tectonics on single plate planets, as well as fluid content in the accessible part of the crust. Cerberus Fossae is an ideal focal point to explore these questions further, answering the question whether habitable pockets might survive over long periods in an otherwise barren world. This results in the following **mission goals**:

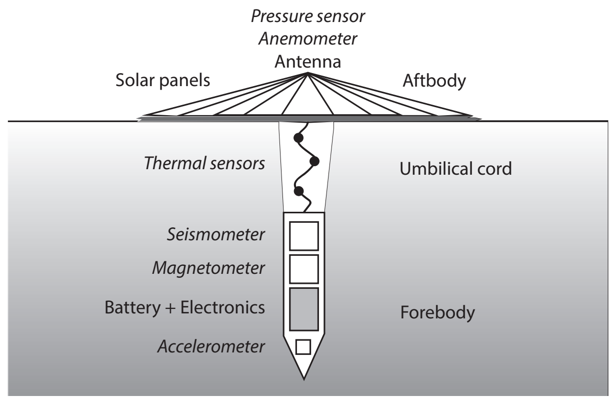

Figure 1: Cross section of one penetrator. The forebody contains a seismometer, a magnetometer, an accelerometer, as well as electronics. The aftbody disconnects during impact and stays above the surface. It is connected to the forebody by an umbilical cord with thermal sensors and contains solar panels and a basic meteorological suite. The seismometer is the main instrument of the mission and well-coupled to the ground. The accelerometer is used to measure ground rigidity during impact.

- **G1: Locate shallow and deep marsquakes with an uncertainly of less than 20 km.** Determine the regional stress field and the driving mechanism behind the opening of C.F.
- **G2: Determine a velocity and attenuation model of the crust and uppermost mantle in the Cerberus Fossae region.** Constrain the temperature gradient in the uppermost 20 km and find the bottom of the fractured, low attenuation layer. Confirm or exclude the existence of a frozen water layer below C.F..
- **G3: Constrain the ground rigidity and thermal diffusivity of the top meter at the landing site.** Dis-

tinguish between fluvial sediments and basalt as a top layer.

G4: Observe wind and air pressure continuously on a regional scale. Refine regional climate models to understand aeolian deposition as seen from orbit.

Instruments

Short period seismometer The seismometer is located in the forebody and well-connected to the ground. The burial and the distance to the aftbody reduce ambient noise (G1, G2).

Accelerometer By measuring the deceleration during impact, the accelerometer determines the rigidity of the upper subsurface (G3).

Pressure and anemometer Build a first regional meteorological network on Mars and distinguish marsquake signals from noise. The Solar panels allow to monitor cloud coverage continuously [17] or constrain times of Phobos eclipses [18] (G4).

EM Sounder or magnetometer Installation of a magnetometer network or concurrent measurement of the electric field would allow for direct inversion for conductivity and therefore mineralogy [19] (G2, G3).

Thermal sensors Determine the thermal diffusivity and from it constrain the material properties at landing site (G2, G3).

Mission trade space: The InSight mission has proven the value of a carefully deployed very broadband seismometer (VBB) [20] to determine the deepest structure [21] and infer the composition of the planet as a whole, whereas local seismicity cannot be reliably located from a single instrument, given the strong scattering and therefore lack of polarization [14]. A seismic network could use arrival times to locate quakes, but the deployment effort of the VBB, including the usage of a robot arm for 90 Sols is prohibitive. The InSight seismic data has shown however that local and shallow marsquakes can be observed well with a short period seismometer with significantly lower installation effort [8]. If the lander has a low wind cross section and good ground coupling, operation from inside the lander is possible.

A soft lander has a significant cost penalty due to the EDL system, which can be avoided by a penetrator [22, 23]. A seismic network can operate successfully with 4 instruments. Reliability requirements can be reduced from the typical '3 σ' values, if loss of one or two landers during EDL is acceptable, which significantly reduces the design and qualification cost of each single lander.

Mission concept: We propose a network of 6 initial penetrators or hard landers spread over the center of Cerberus Fossae, each equipped with a 3 component InSight-SP short period seismometer and a meteorological instrument suite (see above). The penetrators would be separated from the cruise spacecraft during approach of Mars and steer independently towards preprogrammed locations within Cerberus Fossae. Typical landing ellipse sizes of 200x50 km would ensure distribution over the target area, with the goal of having at least 4 successful landings and deployments.

Impact velocities of Martian penetrators can be reduced with moderate parachutes to values of 50-80 m/s, resulting in decelerations below 500g, as shown in the Mars96 concept [24, 22]. Power generation has been Achilles' heel of planetary penetrators, with solar panels being heavy and fragile and radio-thermal-generators being generally unavailable. However, the progress on solar panels has significantly reduced weight and increased stability, which makes it possible to include them in an aft body. We propose to disconnect the forebody mechanically from the surface aftbody, to reduce wind-induced seismic noise and improve ground coupling, similar to the Mars96 concept. We propose a mission duration of one Martian year, which should result in observation of several deeper and $>$ 80 shallow marsquakes. Communication is possible via an omnidirectional UHF antenna and the existing fleet of relay orbiters.

References: **[1]** R. D. Wordsworth. In: (2016). DOI: 10.1146/annurev-earth-060115-012355. **[2]** J. Tarnas et al. In: (2021). DOI: 10.1089/ast.2020.2386. **[3]** D. M. Burr. In: (2002). DOI: 10.1029/2001GL013345. **[4]** J. P. Cassanelli and J. W. Head. In: (2018). DOI: 10.1016/j.pss.2018.04.024. **[5]** W. L. Jaeger et al. In: (2007). DOI: 10.1126/science.1143315. **[6]** W. B. Banerdt et al. In: (2020). DOI: 10.1038/s41561-020-0544-y. **[7]** D. Giardini et al. In: (2020). DOI: 10.1038/s41561-020-0539-8. **[8]** J. F. Clinton et al. In: (2021). DOI: 10.1016/j.pepi.2020.106595. **[9]** N. Brinkman et al. In: (2021). DOI: 10.1029/2020je006546. **[10]** I. M. Service. 2021. DOI: 10.12686/A11. **[11]** R. J. Phillips. Tech. rep. 1991. **[12]** M. Knapmeyer et al. In: (2006). DOI: 10.1029/2006JE002708. **[13]** S. Kedar et al. In: (2021). DOI: 10.1029/2020JE006518. **[14]** M. van Driel et al. In: (2021). DOI: 10.1029/2020JE006670. **[15]** P. Lognonné et al. In: (2020). DOI: 10.1038/s41561-020-0536-y. **[16]** E. L. Scheller et al. In: (2021). DOI: 10.1126/science.abc7717. **[17]** R. D. Lorenz et al. In: (2020). DOI: 10.1029/2019EA000992. **[18]** S. C. Stähler et al. In: (2020). DOI: 10.1002/essoar.10503257.1. **[19]** R. E. Grimm and G. T. Delory. In: (2012). DOI: https://doi.org/10.1016/j.asr.2011.12.014. **[20]** P. Lognonné et al. In: (2019). DOI: 10.1007/s11214-018-0574-6. **[21]** S. C. Stähler et al. In: (2021). DOI: 10.1126/science.abi7730. **[22]** R. D. Lorenz. In: (2011). DOI: 10.1016/j.asr.2011.03.033. **[23]** N. Barba et al. In: (2019). **[24]** Y. A. Surkov and R. S. Kremnev. In: (1998). DOI: 10.1016/S0032-0633(98)00071-3.