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A probabilistic framework for single-station location of seismicity on Earth and Mars

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ABSTRACT

Locating the source of seismic energy from a single three-component seismic station is associated with large uncertainties, originating from challenges in identifying seismic phases, as well as inevitable pick and model uncertainties. The challenge is even higher for planets such as Mars, where interior structure is *a priori* largely unknown. In this study, we address the single-station location problem by developing a probabilistic framework that combines location estimates from multiple algorithms to estimate the probability density function (PDF) for epicentral distance, back azimuth, and origin time. Each algorithm uses independent and complementary information in the seismic signals. Together, the algorithms allow locating seismicity ranging from local to teleseismic quakes. Distances and origin times of large regional and teleseismic events (M > 5.5) are estimated from observed and theoretical body- and multi-orbit surface-wave travel times. The latter are picked from the maxima in the waveform envelopes in various frequency bands. For smaller events at local and regional distances, only first arrival picks of body waves are used, possibly in combination with fundamental Rayleigh *R1* waveform maxima where detectable; depth phases, such as *pP* or *PmP*, help constrain source depth and improve distance estimates. Back azimuth is determined from the polarization of the Rayleigh- and/or *P*-wave phases. When seismic signals are good enough for multiple approaches to be used, estimates from the various methods are combined through the product of their PDFs, resulting in an improved event location and reduced uncertainty range estimate compared to the results obtained from each algorithm independently. To verify our approach, we use both earthquake recordings from existing Earth stations and synthetic Martian seismograms. The Mars synthetics are generated with a full-waveform scheme (AxiSEM) using spherically-symmetric seismic velocity, density and attenuation models of Mars that incorporate existing knowledge of Mars internal structure, and include expected ambient and instrumental noise. While our probabilistic framework is developed mainly for application to Mars in the context of the upcoming InSight mission, it is also relevant for locating seismic events on Earth in regions with sparse instrumentation.
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1. Introduction

Mars' interior is expected to still reflect the differentiation and early planetary formation processes that have been lost on Earth due to mantle convection (Solomon et al., 2005). Investigating the interior structure of Mars has therefore been a high-priority objective for planetary scientists since the Viking missions in the mid-1970s (Anderson et al., 1977). NASA supports the scientific discovery and exploration of Mars with multiple programs, including the InSight (**In**terior exploration using **S**eismic **I**nvestigations, **G**eodesy and **H**eat **T**ransport) Discovery Program mission. InSight will deploy a lander equipped with geophysical, geodetic, and meteorological sensors on the Martian surface (Banerdt et al., 2013), including a single three-component ultra-sensitive very-broadband seismometer (VBB; Lognonné et al., 2012; Mimoun et al., 2012). InSight mission goals include (1) providing one-dimensional models of Mars' mantle and core to within ±5% uncertainty in seismic wave-speeds, as well as three-dimensional velocity models of the crust; and (2) measuring the activity and distribution of seismic events on Mars, including both tectonic

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and impact seismicity (Banerdt et al., 2013). The InSight launch is targeted for May 2018.

The detection and characterisation of seismicity is important to understand the tectonic and possible volcanic activity of a planet. In this study, we develop and verify methods for single-station event-location for local, regional, and teleseismic seismicity on Earth and Mars. To deal with the inevitably large uncertainties associated with these event parameters from a single station, we develop a probabilistic framework, which accounts for both observation and model uncertainties. Aside from characterizing Martian seismicity for InSight and similar future planetary missions, single-station methods have terrestrial applications (Frohlich and Pulliam, 1999), such as for seismic and nuclear (CTBTO) monitoring, particularly in regions with sparse instrumentation or in countries that operate small seismic networks or single stations only (e.g., Agius and Galea, 2011). Single-station methods are also relevant to earthquake early warning (e.g., Kanamori, 2005; Böse et al., 2012).

Seismic data from InSight will become available in early 2019. To verify our event location approach we use both seismic records from stations on Earth and synthetic Martian seismograms. The latter are computed from a full-waveform scheme (AxiSEM; Nissen-Meyer et al., 2014; van Driel et al., 2015) using spherically-symmetric seismic velocity and density models that incorporate existing knowledge on the internal structure of Mars, as well as predicted ambient and instrumental noise characteristics (Murdoch et al., 2015a,b). In this paper we present a novel approach to single-station location. In our companion paper, Khan et al. (2016), we apply this method to marsquake simulations, and extend the approach to simultaneously invert for structure.

1.1. Seismic activity on Mars

Seismic activity on Mars is anticipated to be similar to terrestrial intraplate activity (Anderson et al., 1972, 1977) with a total moment release in-between that of the Earth and Moon (Golombek et al., 1992). Theoretical models for thermo-elastic cooling (Phillips, 1991) and observed surface faults (Golombek et al., 1992; Knapmeyer et al., 2006) predict a Martian annual occurrence of ~50 globally detectable marsquakes with seismic moments of $\sim 10^{15}$ Nm ($\sim m_b = 4$), and ~5–10 times more quakes for each unit decrease in moment magnitude (Golombek, 2002).

Without plate tectonics on Mars, we expect that secular cooling of the planet as described in Phillips (1991) is the driver of sustainable tectonic stress. Independent of this, another source of seismic events on Mars are meteorite impacts, that are expected to constitute ~20% of all observed events, similar to observations on the Moon (Banerdt et al., 2013). The Apollo 14 seismometer detected on the Moon about 100 events per year with ground velocities $>10^{-9}$m/s (Oberst and Nakamura, 1991; Lognonné et al., 2009). The larger mass of Mars suggests 2–4 times more impacts (Banerdt et al., 2013), although the velocity of these impacts will only be half due to smaller orbital velocities and to the additional deceleration in the atmosphere of Mars, which is absent on the Moon (Lognonné and Johnson, 2007, 2015; Lognonné and Kawamura, 2015). In a recent study, however, Teanby and Wookey (2011) find that detectable impacts at teleseismic distances of >60° are likely going to be rare and may occur only once every 10 years; local impacts, on the other hand, are expected to be more frequently detectable. Successful identification and location of meteorite impacts is crucially important to produce ground truth locations that will strongly constrain structural models of Mars. Approximate locations of suspected meteorite impacts will be used as targets for gathering high-resolution orbital images, in order to visually identify and provide exact impact locations. Even though we presently focus on the location problem for marsquakes, we expect our approach to be applicable to locate impacts, provided that at least two seismic phases can be identified.

2. Method

Seismic (point-) source locations are commonly characterized by four parameters: (1) latitude φ, (2) longitude λ, (3) depth h, and (4) origin time t_0. In single-station processing, the problem is often decomposed: absolute event locations (φ, λ) are replaced by epicentral distances Δ and back azimuths Θ *relative* to the single station (e.g., Frohlich and Pulliam, 1999; Magotra et al., 1987). The advantage of this decomposition is that Δ and Θ can be determined independently of each other and be combined at a subsequent stage to provide an absolute event location (φ, λ). With the resulting location, t_0 can then be easily computed from available velocity models.

Estimating the source depth from a single sensor is challenging. Certain secondary phases, such as *PmP*, *SmP*, *pP* or *sP*, are depth-sensitive and if identifiable could potentially be used to infer h. Similarly, cross-correlation techniques or relative amplitudes of body-to-surface wave energy are useful. Though in this study we mainly focus on determining Δ, t_0 and Θ, we will illustrate how depth can be determined from *PmP* or *pP* using the examples of two small local quakes on Earth and Mars.

Single-station locations, as a matter of principle, are associated with large inherent uncertainties that originate from inevitable pick and model uncertainties (e.g. Husen and Hardebeck, 2010), and potential mis-identification of seismic phases. In this study, we address the problem of single-station event location in a probabilistic framework that combines multiple algorithms with the goal to estimate the probability density functions (PDFs), $p(\Delta)$, $p(t_0)$, and $p(\Theta)$, for observing Δ, t_0 and Θ given a set of observed phase picks (and uncertainties) and the polarization of surface and body waves.

In the following sections, we present two single-station algorithms to estimate $p(\Delta)$ [and $p(t_0)$] from picks of seismic phase arrivals, and two algorithms to estimate $p(\Theta)$ from wave polarization. We demonstrate that event location estimates improve significantly through the combination of multiple algorithms, which mathematically corresponds to a multiplication of the respective PDFs:

$$P(X) \propto \prod_{M} p_M(X), \quad X = \{\Delta, \Theta, t_0\}, \tag{1}$$

where M is the method used. The procedure is schematically illustrated in Fig. 1.

2.1. Distance estimation from multi-orbit Rayleigh-waves: $p_{R1\ R2\ R3}(\Delta)$

Rayleigh waves propagate along the free surface of a planet and are characterized by elliptical ground-motions. Their amplitudes decay slower with increasing distance than those of seismic body waves, which spread out in three dimensions from the source. Therefore, Rayleigh waves are typically detectable at much larger hypocentral distances than body waves. Large events may generate Rayleigh waves that travel multiple times around the whole globe before their amplitudes are attenuated below the level of background noise. The first 3 multi-orbit phase arrivals are named *R1*, *R2*, and *R3*, where *R1* propagates along the minor-arc from the quake towards the receiver; *R2* takes the opposite direction around the planet along the major arc; *R3* propagates along the minor arc plus another trip around the great circle path.

Differential times between multi-orbit Rayleigh-wave phase-arrivals can be used to infer epicentral distance Δ and origin time

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