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Joint analysis of Rayleigh-wave dispersion and HVSR of lunar seismic data from the Apollo 14 and 16 sites

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ABSTRACT

Active and passive seismic data from the Apollo 14 and 16 missions are analyzed with the aim of determining robust shear-wave velocity (V_S) profiles of the uppermost lunar strata.

While data from the Active Seismic Experiment (ASE) allow the study of Rayleigh-wave dispersion by means of Multiple Filter Analysis (MFA), data acquired by the Passive Seismic Experiment (PSE) are used to determine the Horizontal-to-Vertical Spectral Ratio (HVSR). These two datasets are jointly analyzed according to state-of-the-art procedures in order to overcome the intrinsic limitations of both methodologies (when considered independently) and with the aim of determining a solution (i.e., the vertical V_S profile) not affected by non-uniqueness of the solution and not based on any *a priori* assumption.

Obtained results appear in general agreement with the early P-wave refraction analyses (a sharp contact between a very soft Regolith and a stiffer overlain layer is apparent) and indicate very low shear-wave velocities and very high *Q* values (low dissipation) also confirmed by a number of seismological studies on moonquakes and meteoroid impacts.

1. Introduction

Understanding the near-surface structure of the Moon is important not only for scientific reasons (e.g., understanding the cratering processes which modeled the lunar surface), but also for possible future technological applications related to mining, geotechnical activities, oxygen production, etc. (Carrier and Mitchell, 1976; Chamberlain et al., 1993; Sherwood and Woodcock, 1993; Hurtado and Velasco, 2010).

Active (Active Seismic Experiment, ASE) and passive (Passive Seismic Experiment, PSE) seismic data collected during various Apollo missions were analyzed by several authors for the reconstruction of both the shallow and deep lunar structure as well as for the study of the lunar seismicity (AA.VV., 1971, 1972; Anderson and Kovach, 1972; Watkins and Kovach, 1973; Kovach and Watkins, 1973; Mark and Sutton, 1975; Bulow et al., 2005; Chenet et al., 2006), while several laboratory measurements were performed with the aim of obtaining an appropriate framework within which lunar data must be interpreted (Talwani et al., 1974; Mizutani and Osako, 1974; Warren et al., 1974; Tittmann, 1972; Tittmann et al., 1975; Stesky and Renton, 1977; Stesky, 1978).

Refraction studies performed on the Apollo 14 and 16 datasets, were performed in order to determine the P-wave velocity profiles of the shallow materials (Watkins and Kovach, 1973; Cooper and Kovach, 1974) and the obtained velocities (V_P of the Regolith equal to about 100 m/s) were generally explained in terms of formation mechanism of the surface soft layers and the anhydrate conditions of the lunar materials, even if we could also speculate that the little consolidation that the lunar materials suffered because of the smaller gravity (gravity on the Moon is about one sixth the gravity of the Earth) could also at least partially be the cause of the observed small velocities.

It is also notable and well-known (e.g., Dainty et al., 1974) the ringy nature of the seismic signals recorded on the Moon which is due to the very high *Q* (quality factors) values (i.e., very low attenuation), likely related to the absence of liquids and gasses in a highly-fractured material and, possibly, to vacuum conditions and high temperature effects (Tittmann, 1972; Dainty et al., 1974; Warren et al., 1974; Tittmann et al., 1975).

The Regolith (e.g., Carrier and Mitchell, 1976) is represented by a layer of unconsolidated debris constituted by fine soil (average density equal to about 1.5–1.8 g/cm^3) occasionally including breccia, rocks and boulders from the bedrock and its thickness generally seems to range from about 5 m on younger *maria* to about 20 m on older *highlands* (AA.VV., 1971, 1972).

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Its peculiar characteristics are due to the complex physical and chemical processes occurring on the lunar surface because of the interaction between the surface materials, the solar wind and the micrometeorites that constantly hit the surface (such processes are often referred to as "impact gardening" or "space weathering"). Actually, small trenches and samples have revealed that the Regolith is highly stratified with many buried soil horizons (Lindsay, 1976).

Although most of the lunar literature necessarily dates back to the 70s, the opportunities provided by recent technical and scientific developments allow the re-processing of lunar data according to methodologies capable of providing a deeper understanding of the formation and evolution of our satellite (Horvath et al., 1980; Khan et al., 2000, 2007; Khan and Mosegaard, 2001; Larose et al., 2005; Chenet et al., 2006; Tanimoto et al., 2008; Oravec, 2009; Schmerr et al., 2011; Weber and Schmerr, 2014). The current study focuses on the reprocessing of some data acquired in the framework of both the active and passive experiments collected during the Apollo 14 and 16 missions. In particular, a joint analysis of Rayleigh-wave dispersion (ASE data) and *Horizontal-to-Vertical Spectral Ratio* (HVSR) (PSE data) is performed with the aim of retrieving the vertical shear-wave velocity profiles at the two landing sites while also considering the effects of attenuation and multiple modes of Rayleigh and Love waves on the H/V spectral ratio.

2. Methodology

In order to determine a robust V_S profile, a joint analysis procedure based on the analysis of the Rayleigh-wave dispersion (from active acquisitions) and the HVSR (from the passive experiment) was implemented. The adopted procedure (also briefly summarized in the following paragraphs) is fundamentally the same adopted for instance in Dal Moro (2010) and Dal Moro et al. (2015).

For the current study, Rayleigh-wave dispersion was retrieved by means of the *Multiple Filter Analysis* (MFA) technique (e.g., Dziewonsky et al., 1969; Bhattacharya, 1983; Luo et al., 2011) for three mutually-correlated reasons:

(i) it can be used to extract the dispersive properties of the medium (defined in terms of group velocities) while considering a single seismic trace;
(ii) compared to the methodologies dealing with the phase velocities, MFA (i.e., the group velocities) can result more sensitive to depict some subsurface features (e.g., Luo et al., 2011);
(iii) likely because of the highly ringy and scattered nature of the data, some tests performed on the lunar data (and not shown for the sake of brevity) suggest that Multichannel Analysis of Surface Waves (MASW – an active technique based on trace correlation, e.g., Park et al., 1998; Dal Moro et al., 2003) does not allow sufficiently-clear analyses (phase-velocity spectra result completely blurred).

It must be also considered that several ASE seismic traces are clipped due to the limited dynamic range of the pioneering equipment used (for the Apollo 14 and 16 missions the equipment was substantially the same and seismic data were acquired by means of a 5 bit A/D converter – see *Apollo 14 and 16 Preliminary Science Reports*, PSR – AA.VV., 1971, 1972).

On the other hand, the *Horizontal-to-Vertical Spectral Ratio* (HVSR) is a classical methodology widely used in seismic-hazard studies and, to some degree, in the estimation of the vertical shear-wave velocity profile (Mark and Sutton, 1975; Horvath et al., 1980; Arai and Tokimatsu, 2005; Dal Moro, 2010, 2011, 2014).

In the following, the most relevant points characterizing the MFA and HVSR methodologies (then jointly exploited) are briefly summarized.

2.1. Analysis of surface-wave dispersion via Multiple Filter Analysis (MFA)

The analysis of surface wave propagation for retrieving information about the shear-wave vertical profile can be performed considering phase or group velocities. When dealing with active multi-channel data, the MASW technique is often used to depict phase velocities (Stokoe et al., 1988; Shtivelman, 2002), while when a single trace is considered, phase velocities cannot be easily determined and, as a consequence, group velocities are computed for instance via MFA (Dziewonsky et al., 1969; Bhattacharya, 1983; Luo et al., 2011).

While analyzing the group-velocity spectra, the biggest problem is related to the complex interlacing of different modes, since group velocities of the higher modes can travel slower than the fundamental one. In order to clarify this point a synthetic model is reported in Table 1 while the related group-velocity spectrum and the modal dispersion curves are presented in Fig. 1.

As can be noted from the plots reported in Fig. 1 (where the theoretical modal *group-velocity dispersion curves* are plotted over the *group-velocity spectrum* – for a complete definition of these two expressions and for an overview on the related issues see Dal Moro, 2014), the various modes that characterize the Rayleigh-wave propagation can interlace in a complex fashion. In fact, differently than the phase velocities, the higher modes can travel with group velocities lower than that of the low-order modes. For the current case, for instance, while for frequencies higher than

Table 1
Model considered for the computation of the synthetic data reported in Fig. 1.

Layer	Thickness (m)	Shear-wave velocity, V_S (m/s)	Poisson
1	0.3	350	0.3
2	0.5	170	0.45
3	0.5	130	0.35
4	2.0	450	0.20
5	2.0	420	0.30
6	5.0	400	0.30
7	10	270	0.30
8	40	600	0.20
Half-space		800	0.20

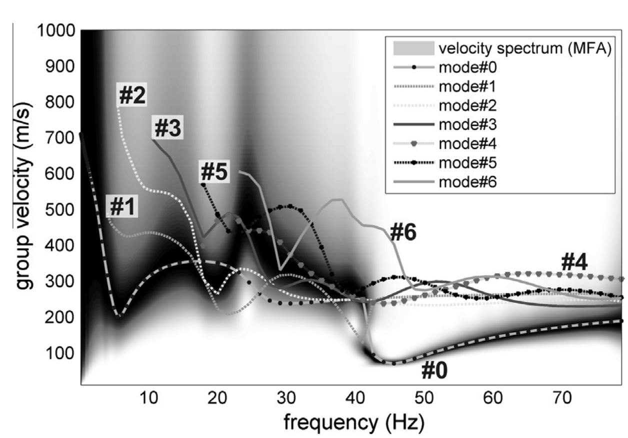

Fig. 1. Group-velocity spectrum (vertical component of Rayleigh waves generated by a vertical-impact source) computed via MFA for the synthetic model reported in Table 1 with, overlaying, the group-velocity modal dispersion curves for the first 7 modes.