NEW TECHNOLOGIES FOR NEW SEISMIC DISCOVERIES ON THE MOON:

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Rationale: The international effort in the return to the Moon will probably allow us to adress several scientific objectives with seismic instruments. These objectives can be listed in three main areas, covering either exploration purposes, Science on the Moon or science of the Moon. A detailled presentation of the results of Apollo and science objectives of future missions can be found in [1,2]. We focus in this paper on the instrumental and technological aspects and show how the improvment in seismic technology will lead to new and exciting discoveries on the Moon in the next decade.

Exploration aspects and SP regional networks: The frequency/size law of meteoroids impacting the Moon and therefore of the associated probability for affecting a future permanent base on the Moon are still not known precisely [3-6]. Figure 1 provides such estimates for different models published in the literature, and shows that impacts of 10 mg (with energy, for 20 km/s comparable to a 5.56 NATO war bullets of 4 gr at 1 km/s) are expected to occur at a rate approximately inversely proportional to the mass with a flux of 10 to 300 impacts in 10 years per km^2, and therefore significant for future long-term lunar bases.

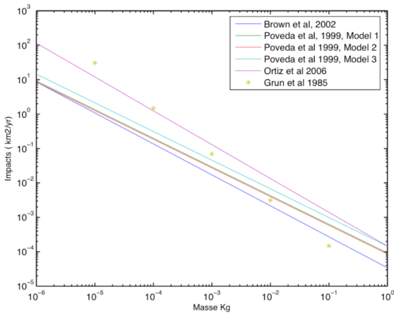

Figure 1: Frequency of micro-impacts. Note the very large dispersion between the proposed models, depending on the technique used for monitoring these impacts.

Very large uncertainties remain therefore in the estimation of these hazards, as most of the small impacts are not observed on the Earth, due to the shielding of the atmosphere and the lack of observable signals. Monitoring these impacts can be done in the future by using a local network of short period micro-seismometers. Figure 2 shows that SP (short period) seismometers with a noise level of 1 ng/Hz$^{1/2}$ will be efficient in detecting small impacts. The operation at high frequency and the local network consideration will enable us to directly measure the impact of the critical 0.01-1 gr meteoroids a few km away. Such an experiment will need the deployment of several (3-4) SPs. Their operation can be limited to the day time and data transfer can be done wirelessly to a central node some few km away. Supposing high integration, each autonomous SP station may have a mass of 1.5 kg, and 5 kg of mass allocation on a rover might therefore enable the deployment of 3 of these SP. Such an experiment might be considered in the ESA MoonNext project.

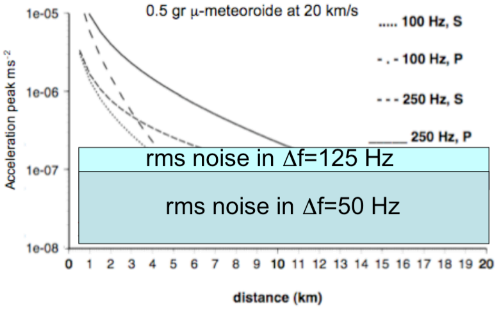

Figure 2: Meteoroid detection on the SP: within 6 km of a central station (about 100 km^2), and with typical frequency inversely proportional to the mass of impactors, we will expect about 20 to 600 impacts of 0.5 gr meteoroids per year. These impacts, for typical short distance propagation conditions on the Moon, will be detected by SP seismometers.

Crustal structure and impact flash detections from Earth: During the Apollo missions, the crust was best studied with active impacts, for which the position and time was known accurately. Recent works have shown that the detection of the light emitted by the meteoroids at impact can now be performed in an efficient way, with relatively small (< 0.5 cm in diameter) and rapid CCD cameras [4,7]. This will allow the detection of kg sized impactors, corresponding to seismic events releasing a seismic impulse of about 2x10^4 Ns (for an impact velocity of about 20 km/s). About 30 of these impacts per year on the Moon at epicentral distances of less than 300 km from any Moon location might be recorded. Larger impacts of about 10^6 Ns will be detected at larger distances, as was done by Apollo, at a rate of about 200 per year. This will provide “calibrated” seismic sources, necessary for precise inversions of the seismic structure of the lunar crust.

Moon internal structure and VBBs global network: The deep internal structure of the Moon remains unknown. This may be addressed by the deployment of Very Broad Band (VBB) seismometers by soft landers or of broad band seismometers by penetrators [8]. Such a network will allow to address key questions, such as the actual size of the lunar core and the detailed structure of the mantle, but also other questions related to the seismic risk to the future lunar base, especially due to the shallow moonquakes [9].

IPGP is collaborating with CNES, the French Space Agency, and ETHZ to develop a Moon version of the Very Broadband seismic sensor (VBB) now selected to fly on the ESA ExoMars mission [10]. Relying on this development, the VBB Seismometer can be adapted to the Moon environment with very minor modifications The current specifications of the SEIS seismometer allow, with a certain number of non-critical modifications, to make it operational on the Moon (e.g., slight modification of the mobile mass). Apart from environmental sensitivity (below about 1 μm /K), the theoretical performance shows that the existing sensor is already better than the Apollo LP and SP instruments, in the bandwidth 10^{-3}-10 Hz. We are currently funded by CNES to increase the performances of the instrument for lunar applications to a level 10-20 times lower than Apollo's background noise, which might be close to the level of microseismic noise associated with the permament impacts on the Moon. In addition to this increase in signal to noise ratio, the use of 24-bit acquisition electronics will also considerably increase the signal dynamics with respect to the Apollo data. Such an instrument is being considered for use on the SELENE-2 JAXA lunar mission as well as for future NASA missions and the ESA Lunar project [11]. Several configurations can be foreseen for the Moon version of the seimometer: as the ExoMars seismometer, the three axis can be in a sphere, for surface deployment. But another possibility for implementation is the use of a mole to bury the seismometer assembly below the surface (see Fig. 4). This configuration offers the advantage of better temperature stabilization of the sensor, especially during the day/night transition.

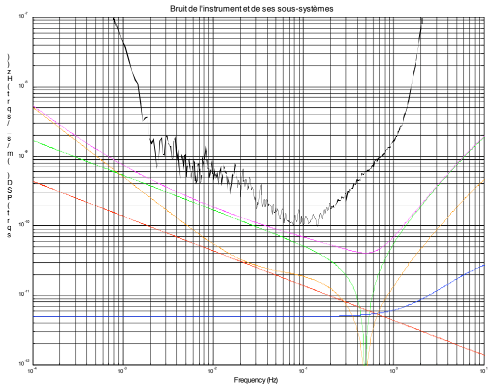

Figure 3: SEIS Moon noise vs. Apollo seismometer noise

Very deep structure, Normal modes and Laser strainmeter: Neither normal modes nor surface waves were detected by the Apollo passive seismic network [12]. Even if a VBB seismometer has an extremely low noise level in the Moon environement, due to the very stable temperature, it will remain challenging to maintain over long time periods performance (below 10 mHz) and to have instrument background levels below 10^{-10} $ms^{-2}/Hz^{1/2}$ for 3-axis instruments than 5 kg in mass. With such an instrument, the detection of the normal modes, even when exited by the largest shallow moonquakes, will be very rare, even if the possibility cannot be excluded for a VBB with a lifetime of more than 5 years operating at frequencies larger than 20 mHz. An alternative option will be based on a superconducting gravimeter [13], or, if mobility can be achieved by a rover or human EVAs, by the deployment of a laser strainmeter. Both instruments could provide an interesting way to detect on a more routine basis these modes at very low frequencies (e.g., below 20 mHz). We provide the expected performances of such instruments and perspectives for normal modes studies, even though they may have to wait for future human Moon missions, due to their low present TRL or installation or maintenance complexity.

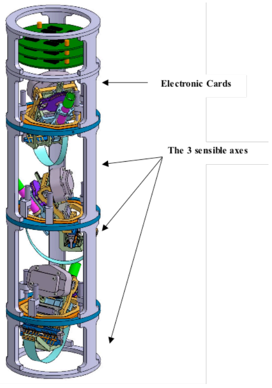

Figure 4: Seismometer mole configuration

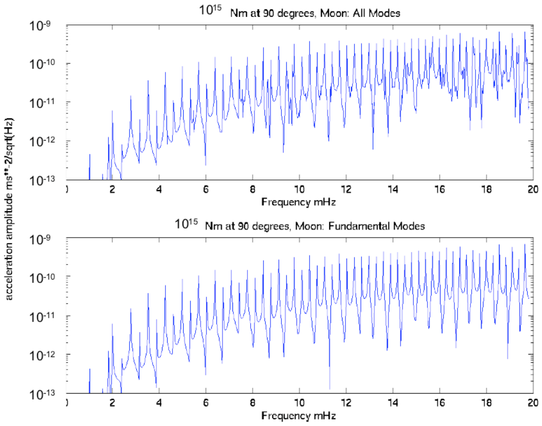

Figure 5: Typical acceleration power spectrum for modes excited by a 10^{15} Nm moonquake, a seismic moment comparable to the largest quake detected by the Apollo Network.

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