Electronic Supplement to:

Lunar Seismology: a data and instrumentation review

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This is a collection of resources for lunar seismology.
The files are archived at Zenodo, with DOI 10.5281/zenodo.1463224
https://zenodo.org/record/1463224

S1: Location Parameters

The file contains parameters describing the location of the Apollo passive seismometers, including longitude, latitude, elevation, azimuth of the horizontal seismometer components and distance between stations. The location parameters have been updated using data from Lunar Reconnaissance Orbiter (Wagner et al., 2017). The horizontal components were intended to point north (MH1) and east (MH2). However, S12 and S16 were misaligned.
station_parameters.csv
station_parameters.README

S2 - Deep Moonquake Stacks

The following files are processed deep moonquake stacks from three independent sources in miniSEED format (Nakamura 2005; Lognonné et al., 2003; and Bulow et al. 2005/Bulow et al. 2007). See the main document for details about the processing.

Nakamura2005_deep_moonquake_stacks.zip
Lognonne_et_al_2003_deep_moonquake_stacks.zip
Bulow_et_al_2007_deep_moonquake_stacks.zip

The authors of Lognonne et al. (2003) carried out different runs for the stacking process. The folders *st* and *st88* refer to these runs.

The Nakamura (2005) stacks were recorded as components 0, 1, 2 … 11. Stacks 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11 correspond to S12 (MHX), S12 (MHY), S12 (MHZ), S14 (MHX), S14 (MHY), S14 (MHZ), S15 (MHX), S15 (MHY), S15 (MHZ), S16 (MHX), S16 (MHY) and S16 (MHZ) respectively. Clusters A12, A79 and A98 had only 6 or 9 components. We do not know which stations each numbered trace maps to. We therefore leave the components as numbers.

S3 - Lunar Catalog from Various Sources

The following file contains arrival-time catalogs from six independent sources, as well as estimates of event time and location where available. The catalogs are provided as an Excel spreadsheet, as a QuakeML file and in ZMAP format. QuakeML is an XML representation of seismological data. ZMAP is a format which outputs 10 or 13 columns, with NaN in the column if no value is available.

Nunn19_LunarCatalog_v1.xlsx
Nunn19_LunarCatalog_v1.xml
Nunn19_LunarCatalog_v1.zmap

The file to convert from the .xlsx to .xml format is here:
excel-to-quakeml.py

The file can be changed form the .xml file to many other standard formats via the ObsPy function obspy.core.event.Catalog.write() method.

The ObsPy obspy.core.event.Catalog.**filter()** method **does not work** with this catalog. This is because it relies on an associated event, and the picks do not have an associated event. Therefore, for most purposes it is necessary to loop through the events and filter the pick times instead.

S4 - Extensive Lunar Catalog from Nakamura et al. 1981 and updates

The catalog was originally published in Nakamura et al. (1981), and has since been updated. It is provided in QuakeML format. The original catalog provided pick times to the start of each minute (the minute mark), and did not associate events to locations or source times. We create a P-arrival pick to the nearest minute for each station, when the catalog indicates that the signal could be read at that station. This does not necessarily indicate that a P-arrival could be clearly distinguished as a separate phase.

LunarCatalog_Nakamura_1981_and_updates_v1.xml

Since the picks are only to the start of each minute, the pick error is at least 60 s.

Note that it is not possible to use the ObsPy obspy.core.event.Catalog.filter() method (the easiest way to find events within a catalog) with this catalog. This is because the filter relies on the time or location of the event. Therefore, it is necessary to loop through the events and filter the pick times instead.

The original catalog files are also included:
levent.1008c
levent.1008c.README
levent.1008c.README2

The file which creates the .xml file is:
import_LunarCatalog_Nakamura_1981_and_updates_v1.py

S5 - Attenuation Parameters from Gillet et al. (2017)

Moonquakes have a characteristic shape, where the maximum energy rises slowly to a maximum, followed by an even longer decay time. The following file is a table of the times of arrival of the maximum energy t_{max} and the coda quality factor Q_c.
tmaxtd.csv
tmaxtd.csv.README

S6 - Low-Level Requirements for Future Seismic Missions to the Moon

We outline minimum requirements for future lunar missions to the Moon. These requirements are particularly relevant to future missions which intend to share data with other agencies, and set out a path for an International Lunar Network, which can provide simultaneous multi-station observations on the Moon.
LowLevelRequirements_InternationalLunarNetwork_v1.0.xlsx
LowLevelRequirements_InternationalLunarNetwork_v1.0.pdf

S7 - Jupyter Notebook to plot the transfer functions

This Jupyter Notebook plots the transfer functions for all experiments:
plot_transfer_functions.ipynb
This Jupyter Notebook describes and plots the logarithmic compression required for the Active Seismic Experiments and the Lunar Seismic Profiling Experiment:
plot_logarithmic_compression.ipynb
The directory includes the calibration data for the ASE and the LSPE, and the notebooks plot these data.
For more information about how to setup a notebook, see http://jupyter.org/. The files can be viewed as html files:
plot_transfer_functions.html
plot_logarithmic_compression.html
These files are zipped within **transfer_notebook.zip.**

S8 - Block Diagrams

Block diagrams for the mid-period seismometer (originally referred to as the long-period seismometer) and short-period seismometer reproduced from Teledyne (1968):
Teledyne_1968_Figure_4-2_Mid-Period_Block_Diagram.png
Teledyne_1968_Figure_4-5_Short-Period_Block_Diagram.png
Block diagram for the Lunar Surface Gravimeter reproduced from Weber (n.d):
Weber_Figure_2_Lunar_Surface_Gravimeter_Block_Diagram.jpg

S9 - Artificial Impacts

The file **ImpactParameters.xlsx** contains a list of the Artificial Impacts. The file has been compiled from a number of sources, which include the original mission reports, https://history.nasa.gov/SP-4029/Apollo_18-29_LM_Lunar_Impact.htm, and https://history.nasa.gov/SP-4029/Apollo_18-26_S-IVB_Lunar_Impact.htm. Several of the craters have been found and mapped using images from Lunar Reconnaissance Orbiter (e.g. Plescia et al 2016).

S10 - Current Data Availability

Passive Seismic Experiment
ALSEP data are currently available from the Data ARchives and Transmission System (DARTS) website of the Japan Aerospace Exploration Agency (JAXA):
https://www.darts.isas.jaxa.jp/planet/seismology/apollo/index.html
This repository contains copies of the original Exabyte files. It also includes these files decoded into ASCII format. This retrieval system contains all the Passive Seismic Experiment data from the Apollo 11, 12, 14, 15 and 16 sites, and the 'Passive Listening Mode' data from the Lunar Surface Profiling Experiment and the Lunar Surface Gravimeter experiment performed at the Apollo 17 site.

Active Experiments
The repository also contains the Active Seismic Experiment and the Lunar Surface Profiling Experiment. This includes the recordings of the thumper shots from Apollo 14 and 16, and the three grenade shots from Apollo 16. The LSPE data contains the eight explosive packages at Apollo 17. The data can be downloaded in SEG-Y format.

Lunar Surface Gravimeter (LSG)
Unlike the other scientific data from Apollo, data from the Lunar Surface Gravimeter (LSG) were not submitted to the National Space Science Data Center for archiving (Lauderdale et al. 1974).

As a result, most of the LSG data were never released, and remain unavailable. After March 1976, raw data for all the experiments were transferred to the University of Texas for processing

and archiving. Due to a recent recovery operation, LSG data are currently available from March 1976 to August 15, 1976 and again from April 25, 1977 to September 1977 (from August 15, 1976 to April 25, 1977 the instrument was not recording due to a high-bit operation for another instrument). Additionally, the raw LSG data are available from IRIS-DMC and the NASA Space Science Data Coordinated Archive (NSSDCA ID: PSPG-00739).

Additional resources for all experiments are available from the NASA Space Science Data Coordinated Archive (NSSDCA ID: PSPG-00739).

S11 - Response Files

The file **Dataless_SEED.zip** contains an xml response file **XA.1969-1977_updated_2019.xml**. It also contains a file XA.1969-1977_original.dataless which was originally produced by researchers at IPGP.

XA.1969-1977_updated_2019.xml contains changes to the station components, station locations and elevations. It also has the updated times when the instruments were operating in peak or flat mode.

The new file uses the convention MH1, MH2 for the X and Y components respectively. X should point north, Y should point east.
This is not the case for all stations. The correct azimuth is included in the file.

The site locations have been updated with values from Wagner et al., 2017.

Station elevation - updated from 0.0 meters to the values given by the
following website:
http://www.lroc.asu.edu/featured_sites/

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