Applying new seismic analysis techniques to the lunar seismic dataset

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Apollo 17 astronaut returning to rover, source: NASA

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Apollo lunar seismic datasets

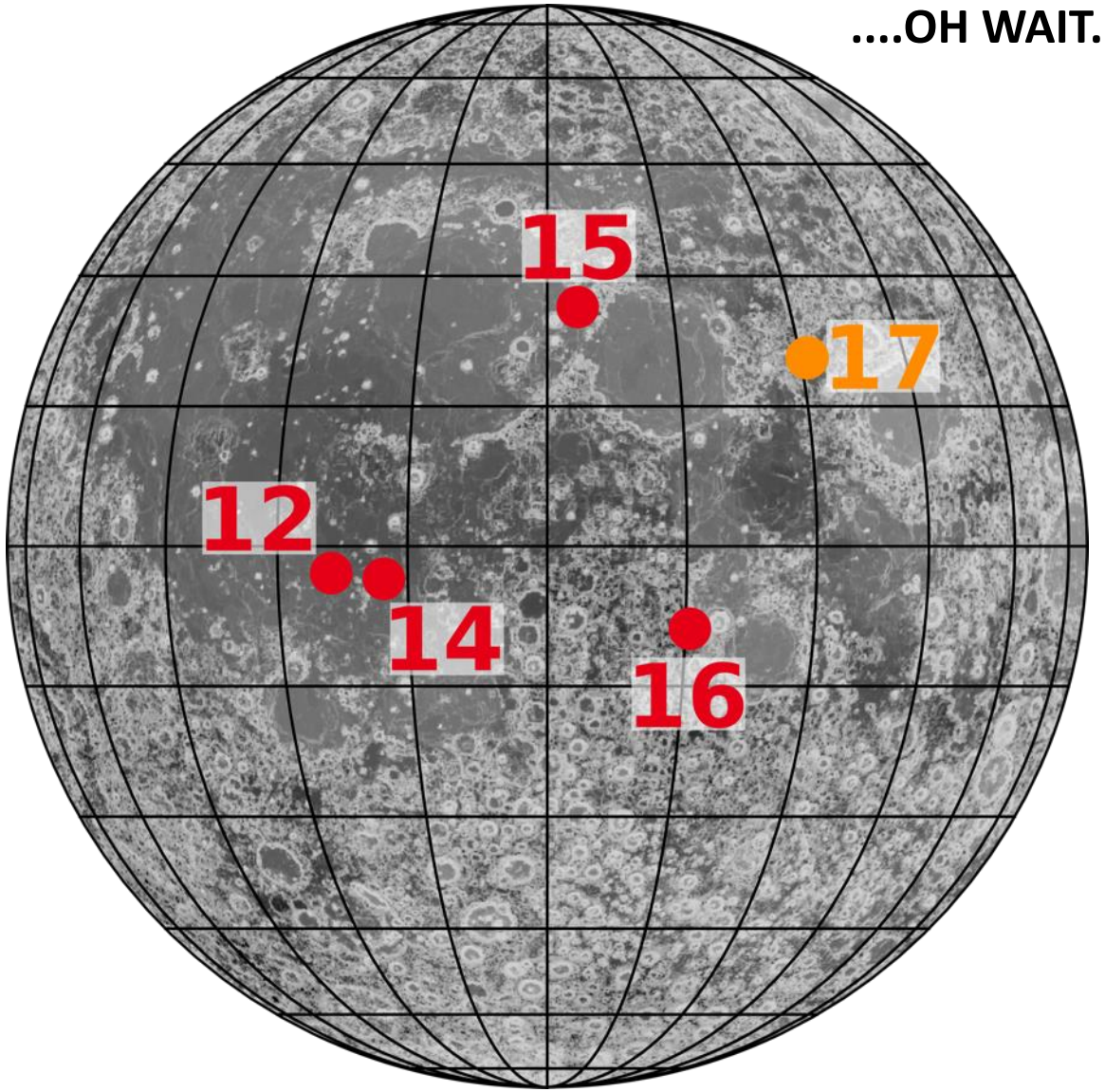
THAT'S NO MOON….
….OH WAIT….

1. A network of **4 passive seismic stations** operated on the Moon (1969-1977)

2. Continuous geophone and gravimeter data available at station **Apollo 17**.

3. Objective is to apply new seismic analysis techniques to this dataset to learn more about the Moon's internal structure.

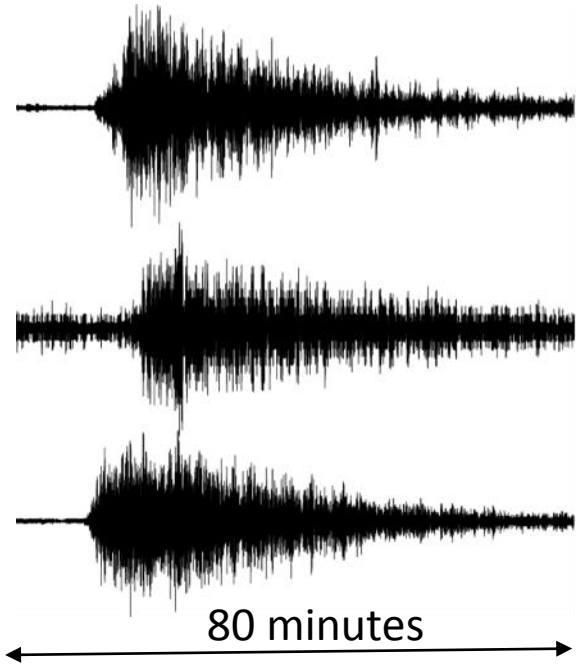
4. Work is partially motivated by the InSight mission to Mars, as new techniques which work on Moon might also work on Mars.

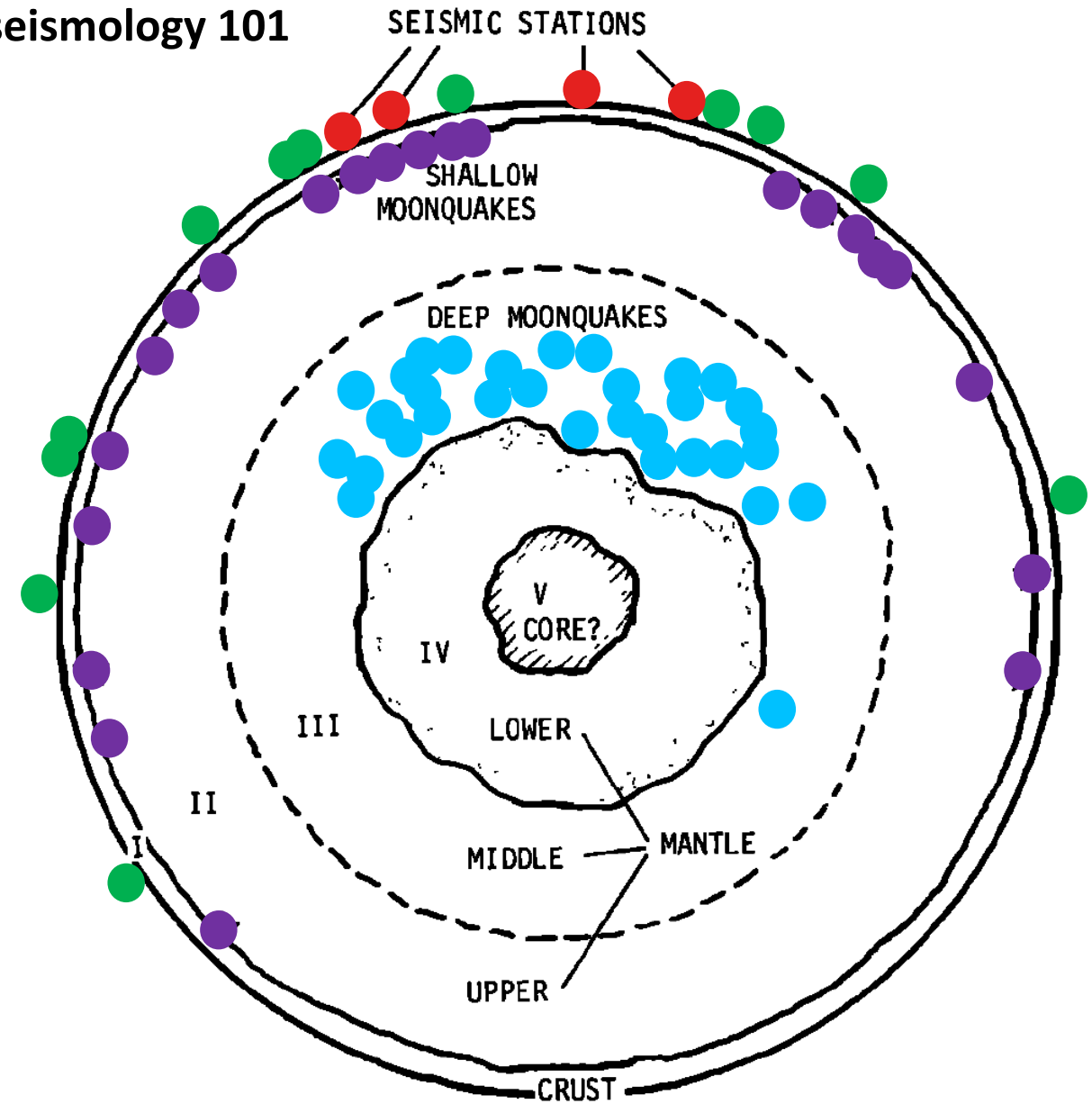


Lunar seismology 101

1. Lunar catalog consists of ~13,000 events
   - Deep moonquakes
   - Shallow moonquakes
   - Meteorite impacts
   - Thermal events (not shown)

2. Moonquake data is poor by puny earthling standards

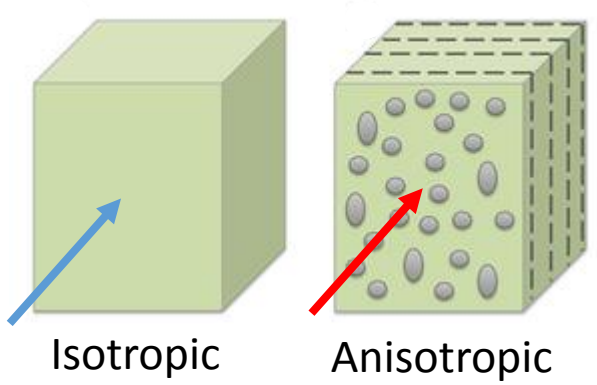




Modified from Nakamura 1983 JGR

New seismic analysis techniques being applied in this project

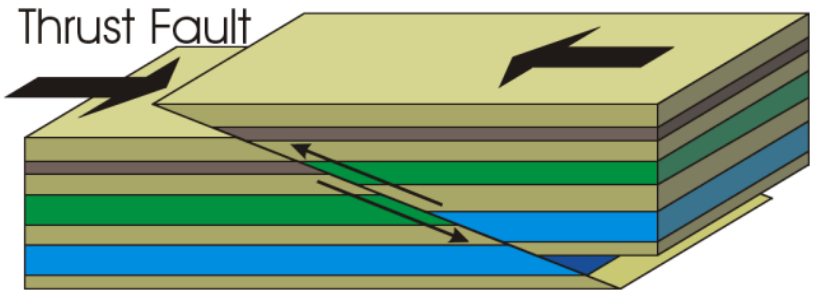
1. Moonquake detecting/classification based on a pattern recognition tool based on "Hidden Markov Models"



2. Anisotropy measurements of the lunar mantle/crust using "shear-wave splitting"

3. Focal mechanism information using a probabilistic (Bayesian) technique to quantify uncertainty.

   Only have time to properly discuss one of these



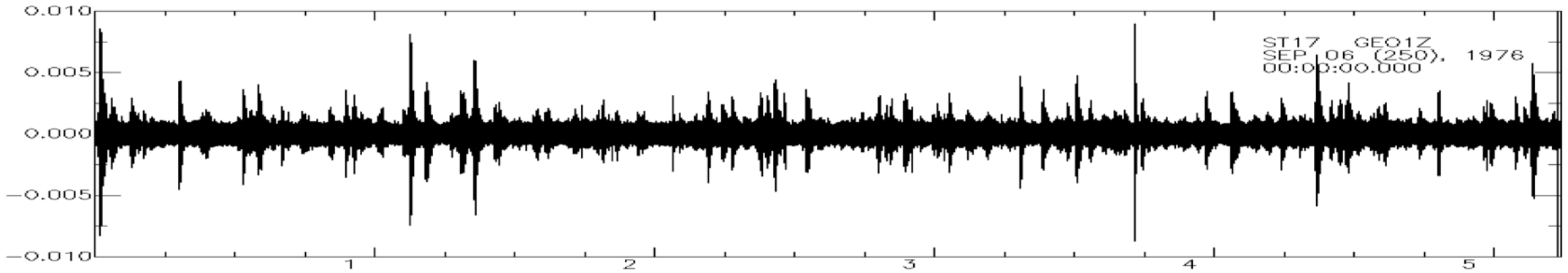
Following sections will go into (1) in more detail + preliminary results

Image sources: Wikimedia group (Creative Commons)

Event detection using Hidden Markov Models on Apollo 17 dataset

1. To our knowledge an event catalog does not exist for the Apollo 17 “listening mode” geophone data recorded between 1976/1977.

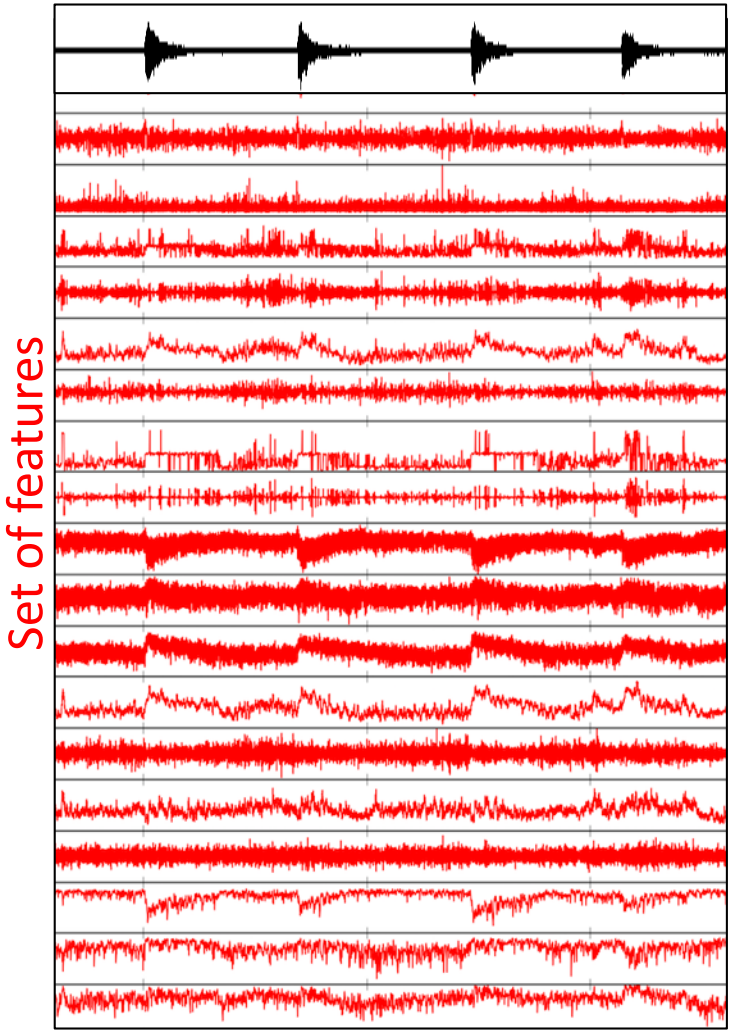
2. Good reason for this, this is 6 hours of filtered listening mode data:



3. Ideal target for “Hidden Markov Models”. This technique allows us to automatically build an earthquake catalog without human effort being required, and does classification automatically.

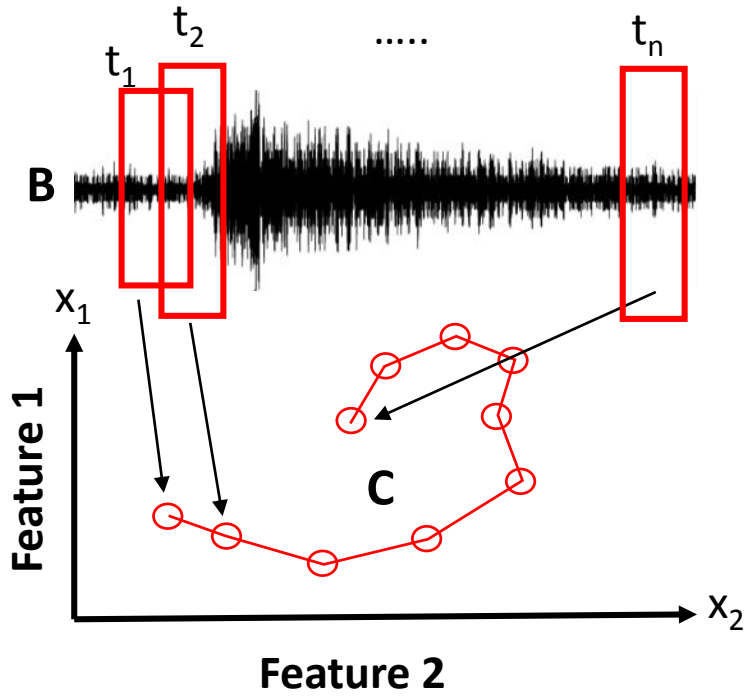
4. Has been recently and successfully applied to Apollo 16 by Knapmeyer-Endrun et al. 2016

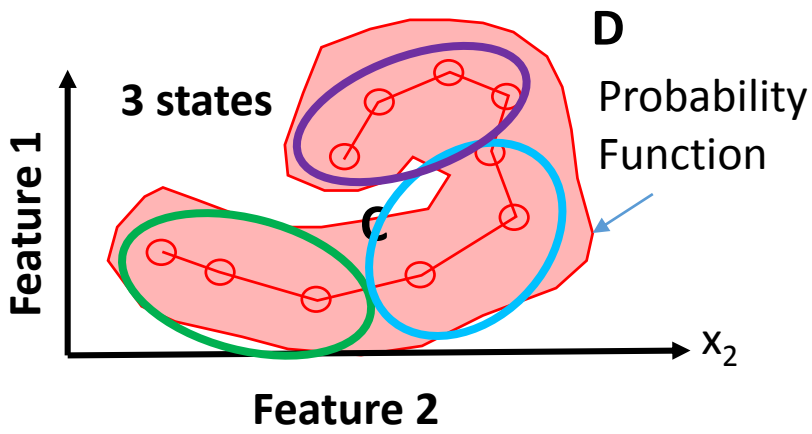
A **Seismic data stream**



How HMM's work

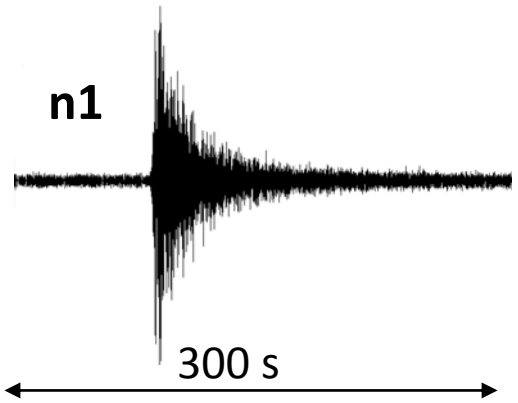
1. A continuous data stream can be represented as a set of features (**A**)
2. Features for a given event (**B**) change over time with respect to one another
3. Their evolution traces unique path in n-dimensional feature space (**C**)
4. The path is then modelled as a sequence of multidimentional PDF's (**D**)
5. This sequence can be searched for to detect and classify other broadly similar events.



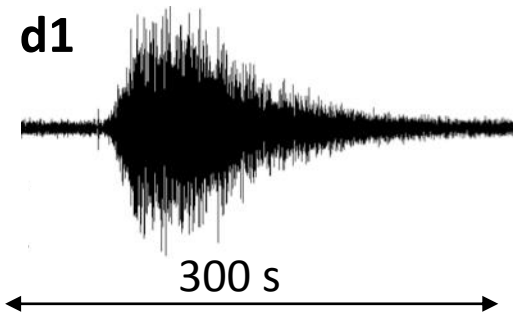


Event detection

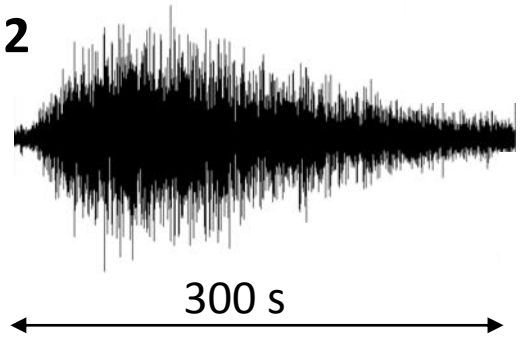
1. Apollo 17 dataset was scanned for “interesting events” to be event templates:



Fast ”risetime” of ~3s
Short duration

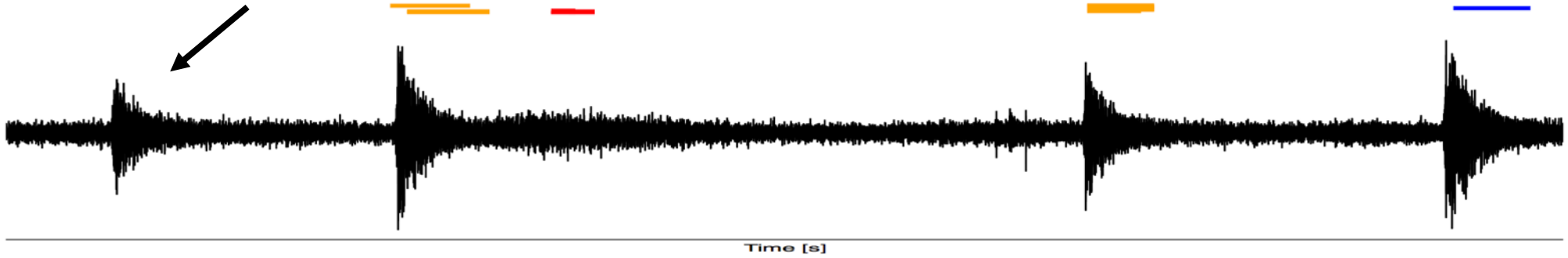


Medium ”risetime” of ~10s
Medium duration



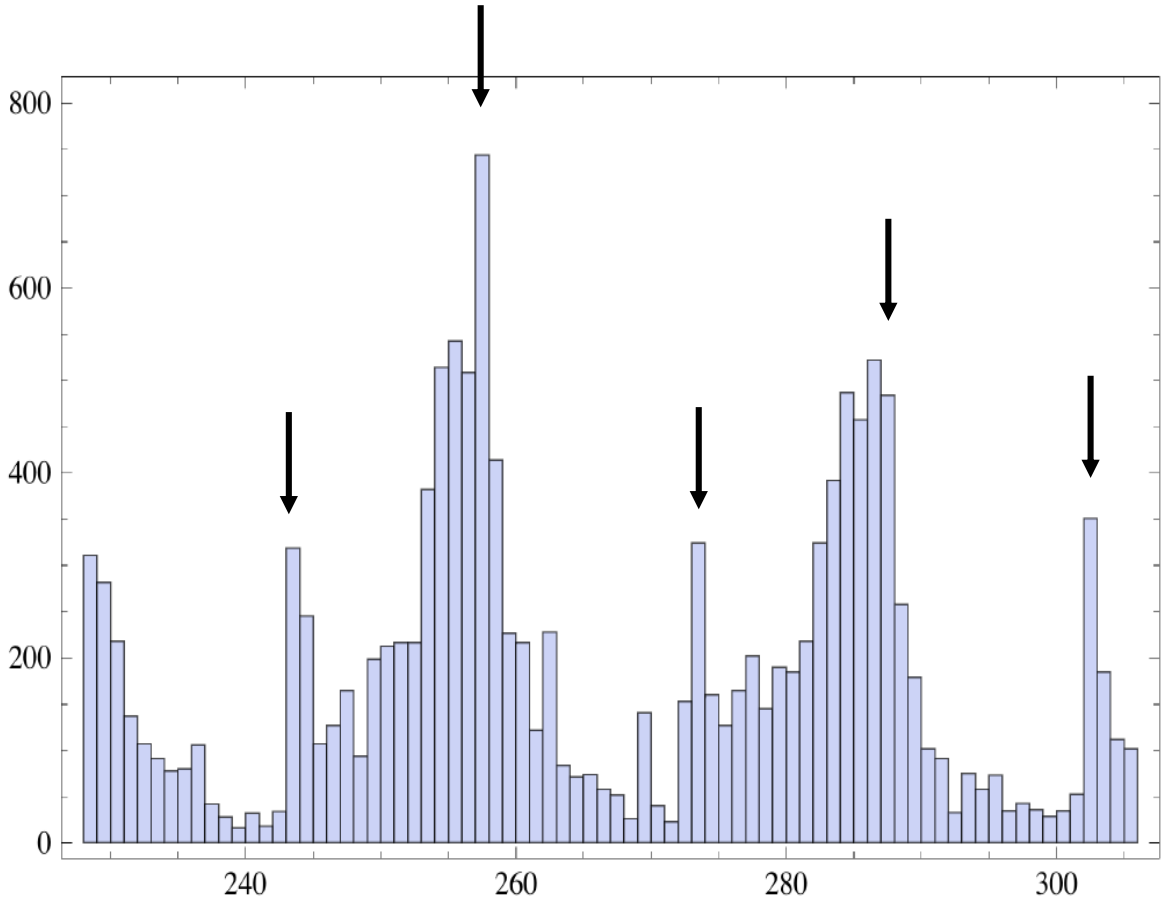
Long ”risetime” of tens of seconds
Long duration

2. Templates were run against continuous database, which detected and classified events, e.g.



3. There are a lot of missed events and questionable detections, the code requires further optimization.

Histogram of all events

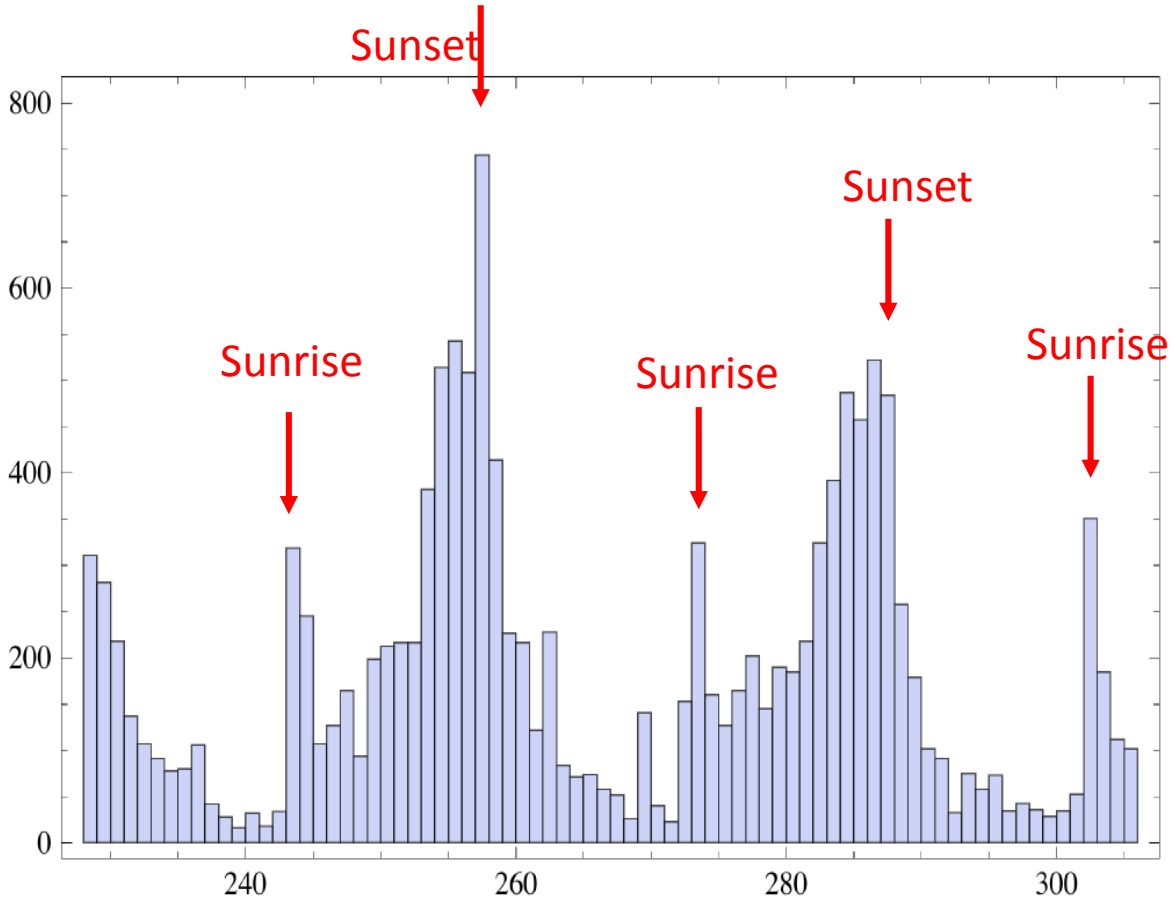


1. Total of 14,338 detections in a 2.5 month period
    1. 10,004 d1 detections
    2. 672 n1 detections
    3. 3662 d2 detections

2. Looking at histogram peaks are evident at regular intervals

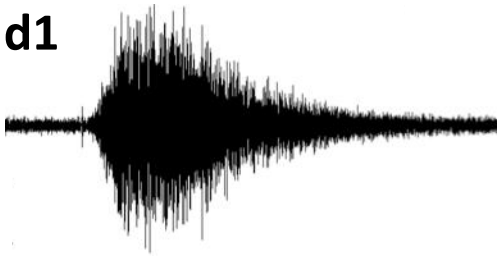
Histogram of all events

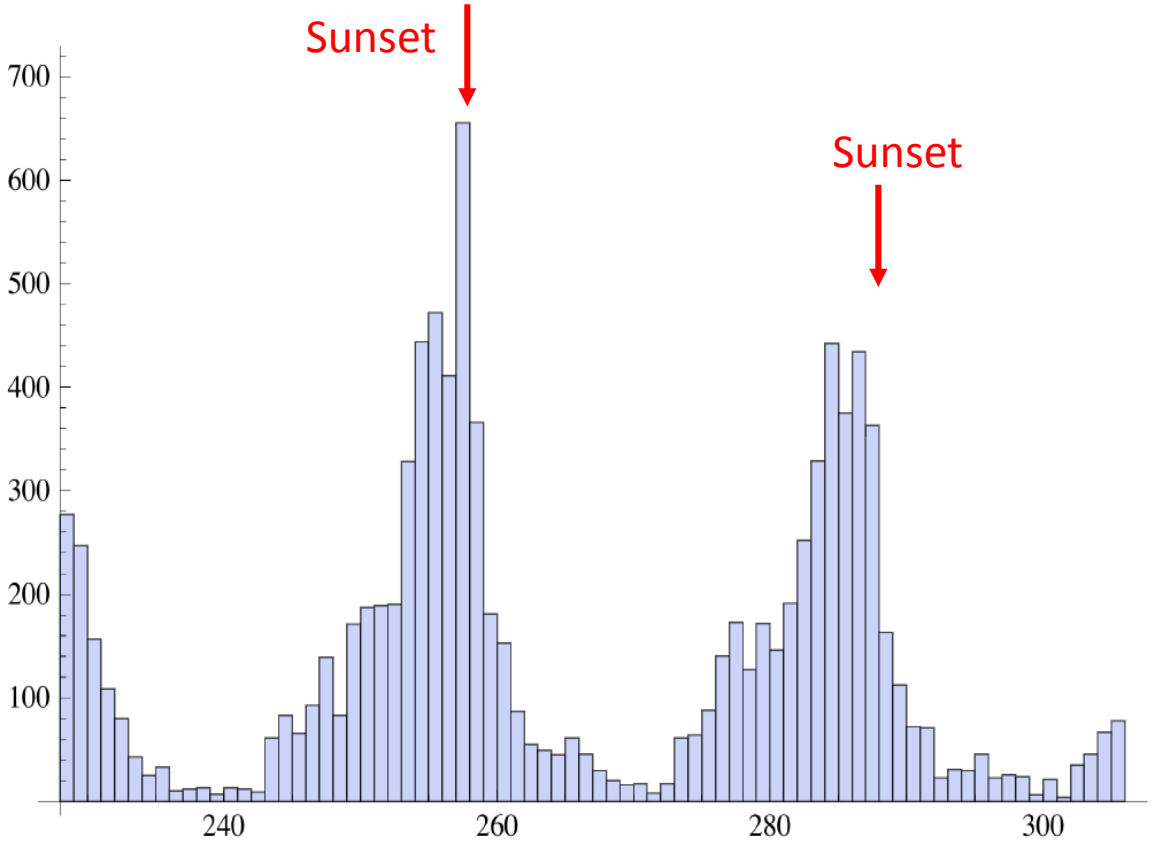
1. Cross-checking with historical moon phases reveals peaks are associated with sunrise/sunset



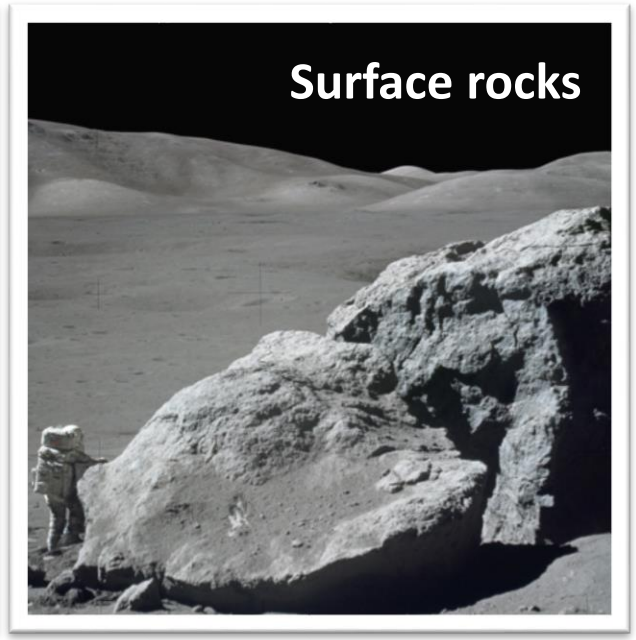
Sunrise **Sunset**

Histogram for d1 events



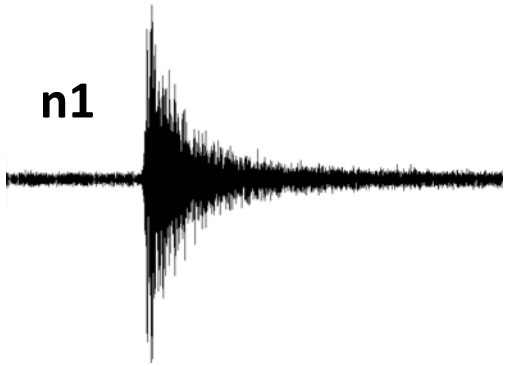


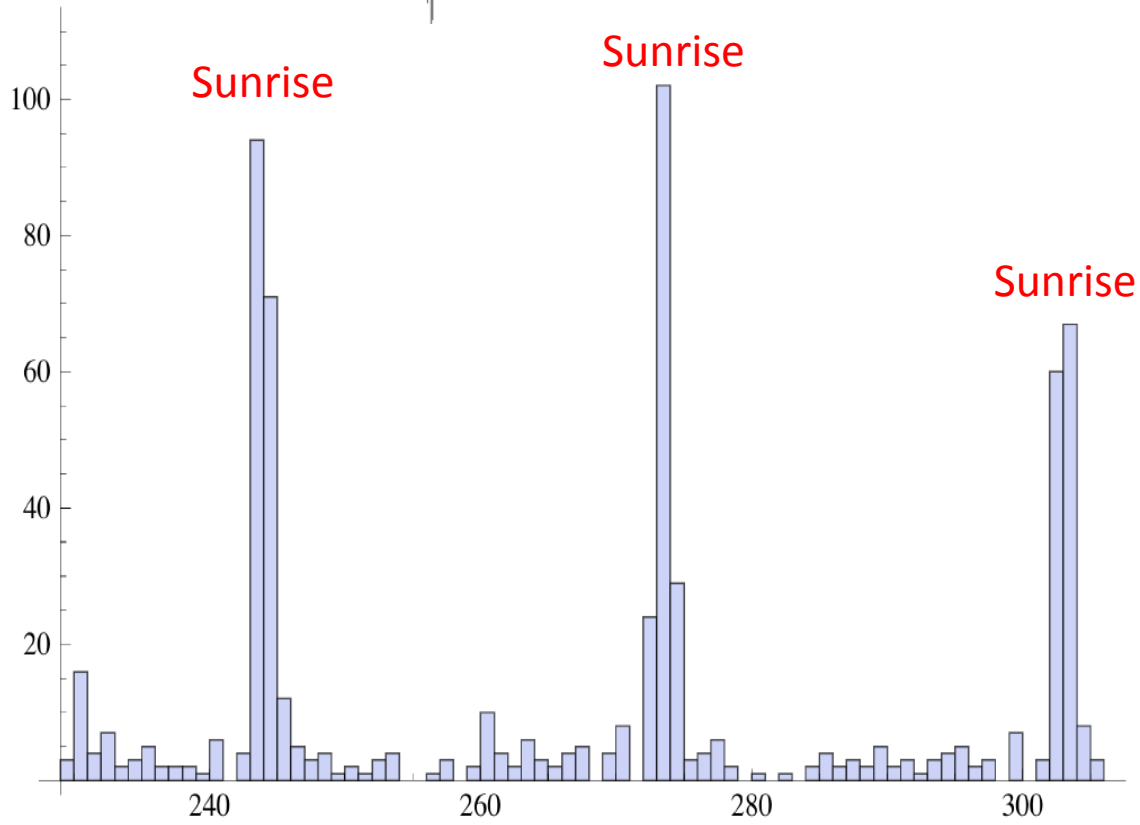
1. Event class d1 shows strong diurnal behavior
2. Only around sunset, no peak at Sunrise.
3. These are probably small thermal moonquakes in the regolith.



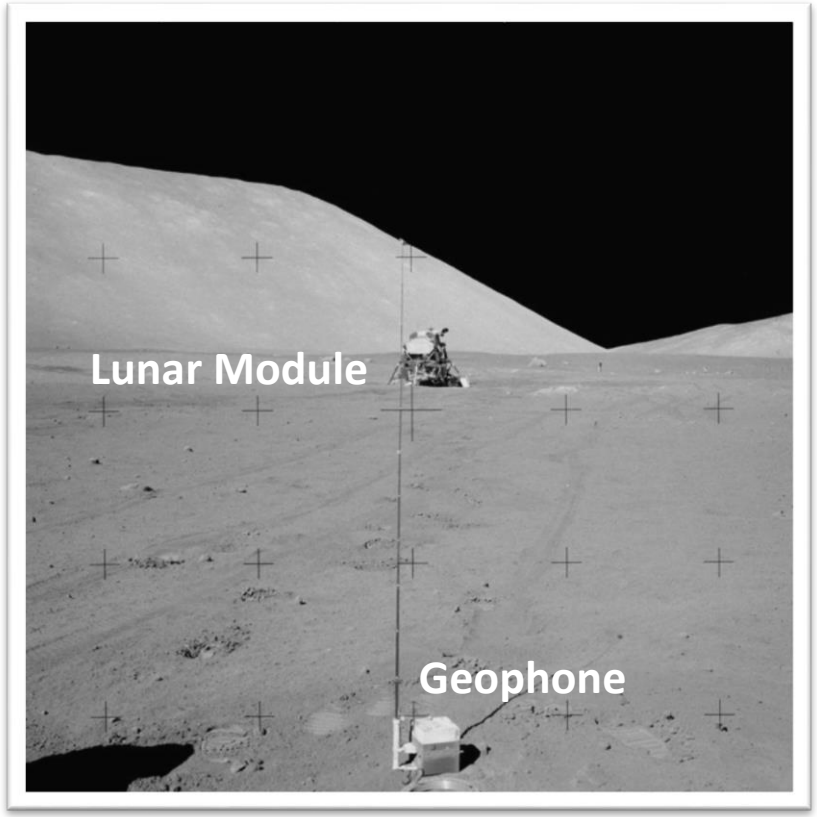
Lunar topsoil and rocks, source: NASA

Histogram for n1 events



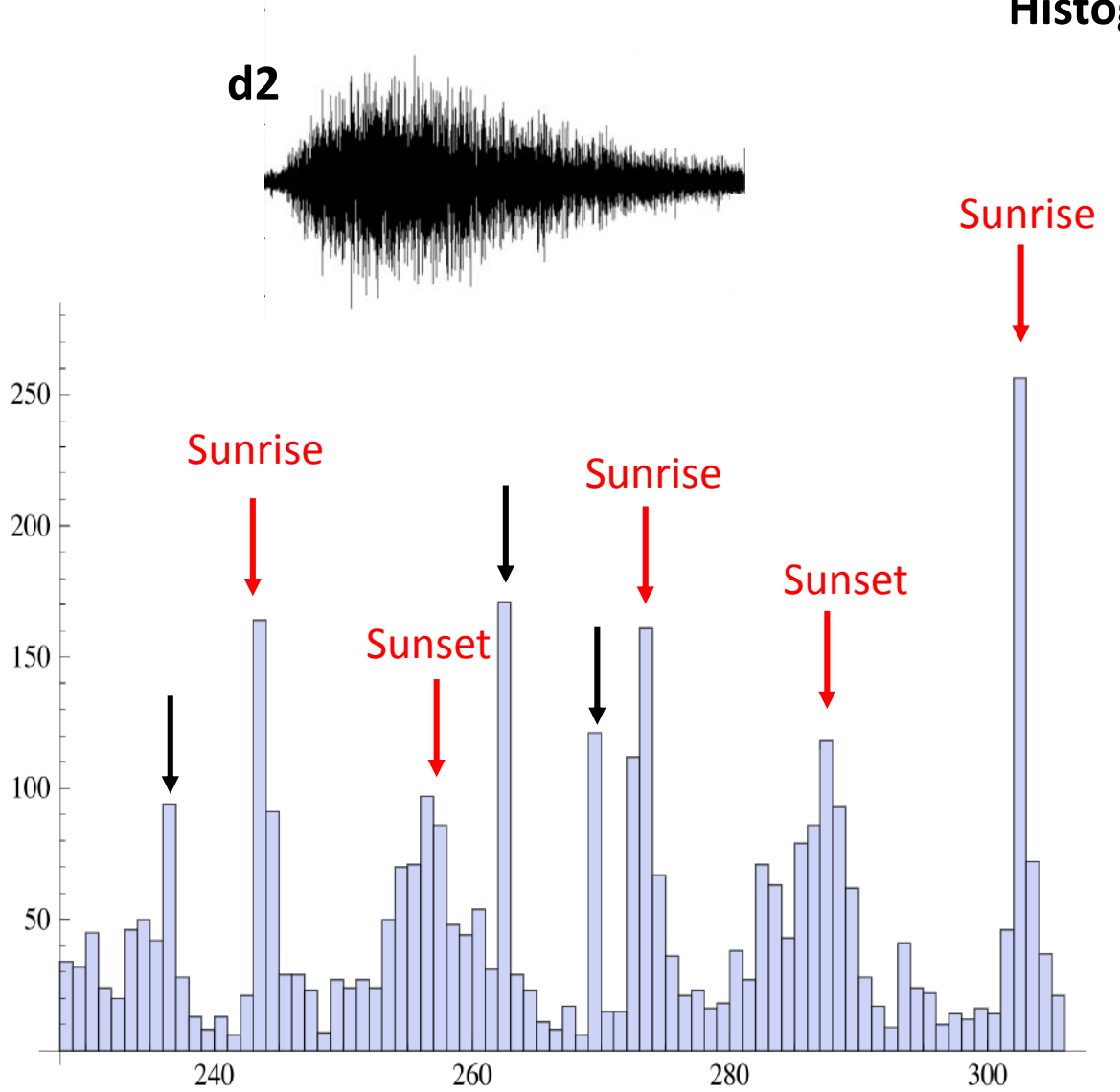


1. Event class n1 has localised peaks at sunrise from a nearby source (e.g. lunar module).



Apollo 17 geophone and lander, source: NASA

Histograms



1. Event class d2 has peaks associated with both sunrise and sunset.
2. Possible we are getting incorrect class detections (n1 and d1 events), further QC required to check.
3. Possible that we are seeing something else in the signal, e.g. 3 other peaks in data.
4. Currently no preferred interpretation for these events.

Future work

1. Continue detecting/classifying Apollo 17 geophone events
    1. Refining parameters should result in more detections
    2. Will be many times larger than the Apollo seismic catalog when finished

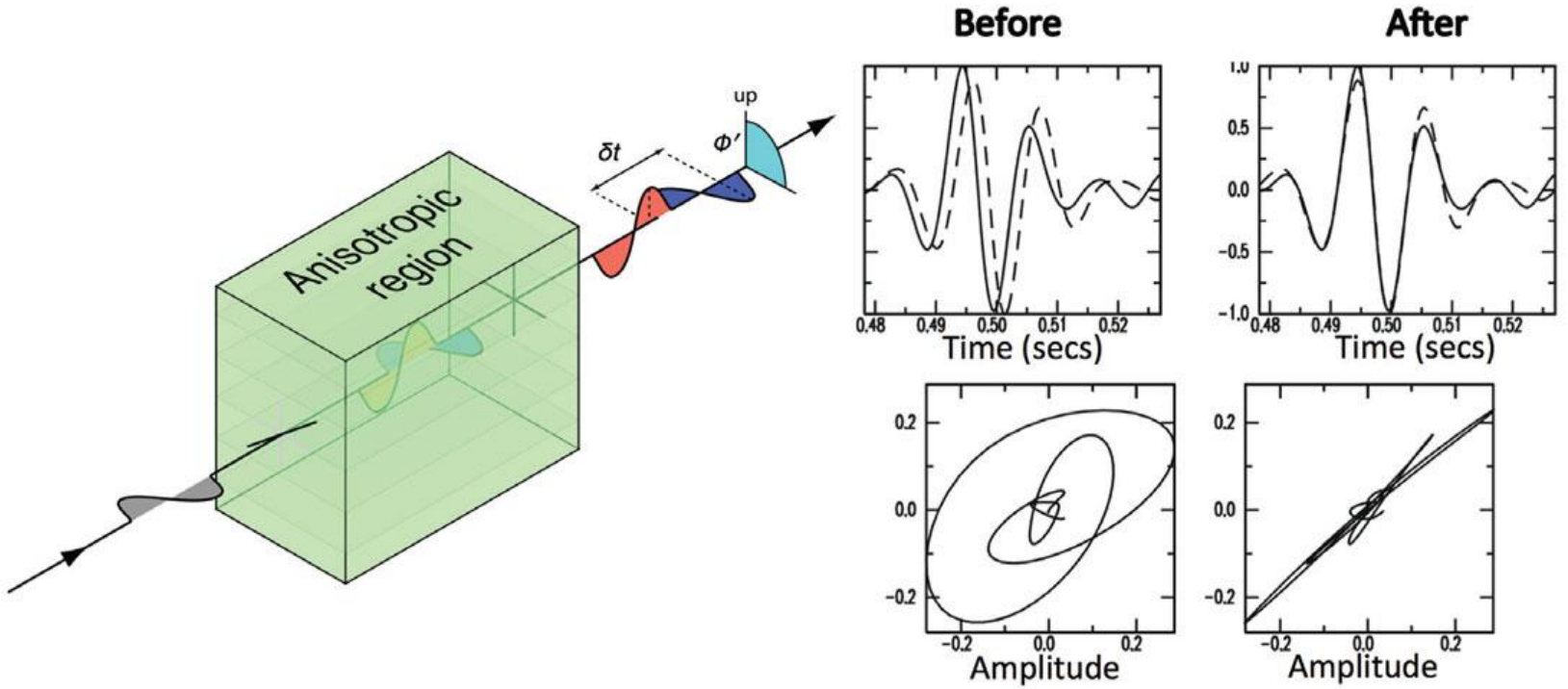
2. Detect/classify events using Apollo 17 gravimeter data as well, and compare to recently published results.

3. Extend HMM to the full Apollo dataset when SEED data is available. Very interested in talk to group who is involved in the conversin!

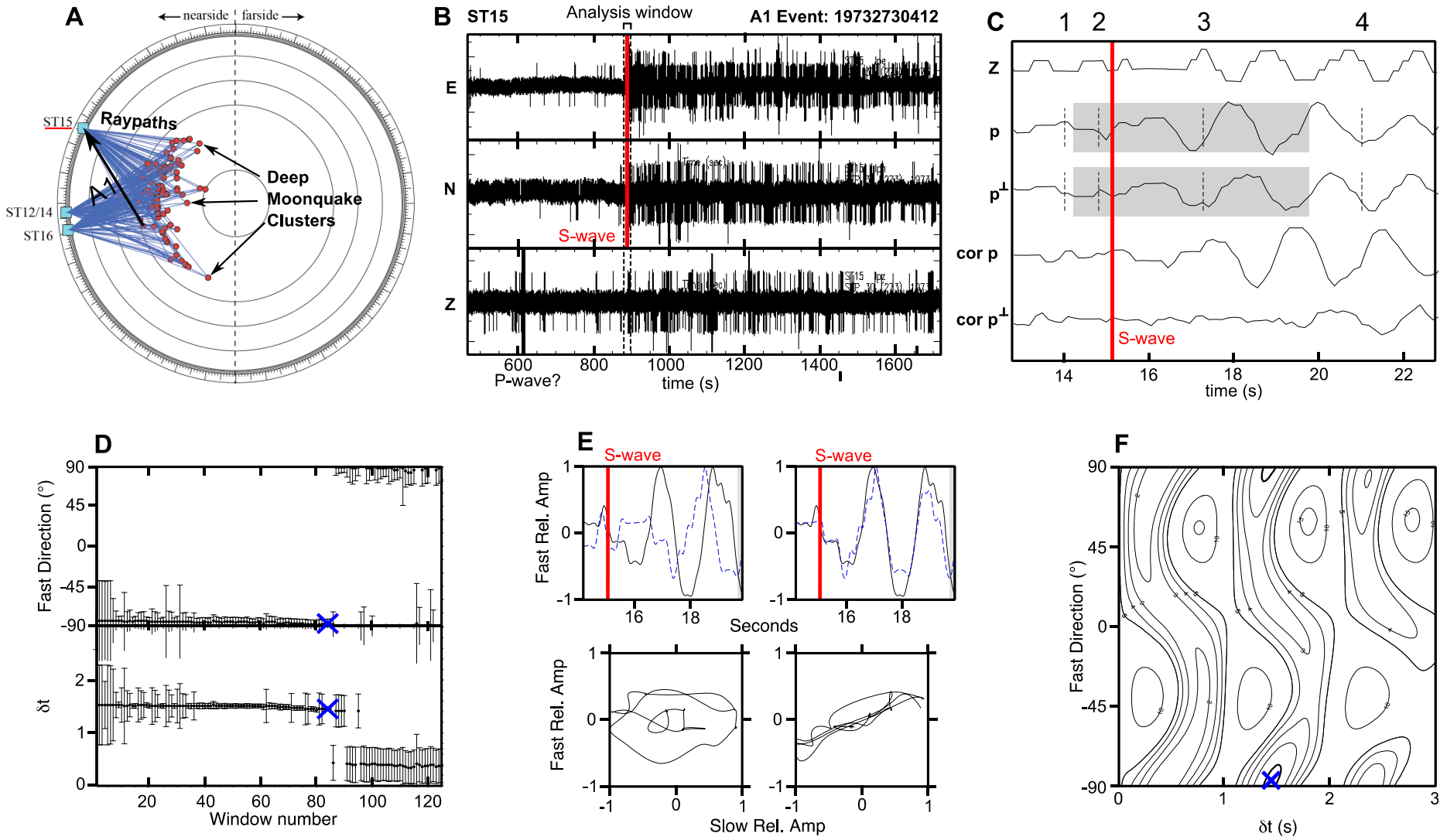
BACKUP SLIDES

Shear-wave splitting measurements

1. Continue detecting/classifying Apollo 17 geophone events, and move onto Apollo 17 LSG data….



First shear-wave splitting measurement of Lunar data



Results fast: 93.0 +/– 5.0 (°) δt = 1.453 +/– 0.038 (s)