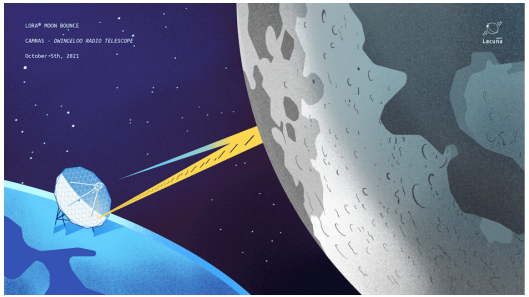


LoRa to the moon (and back)

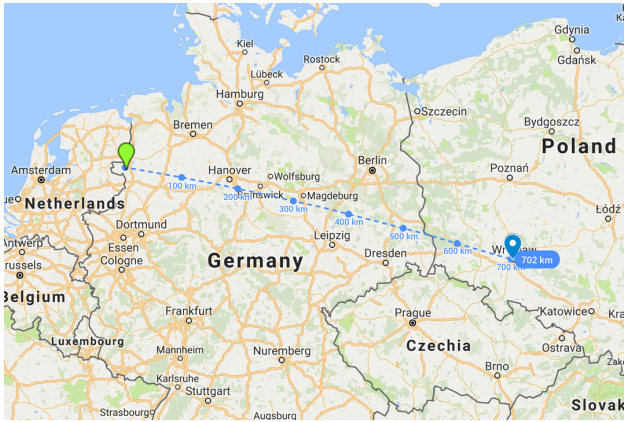
Preliminary Results

Thomas Telkamp, Tammo Jan Dijkema, Jan van Muijlwijk, Frank Zeppenfeldt

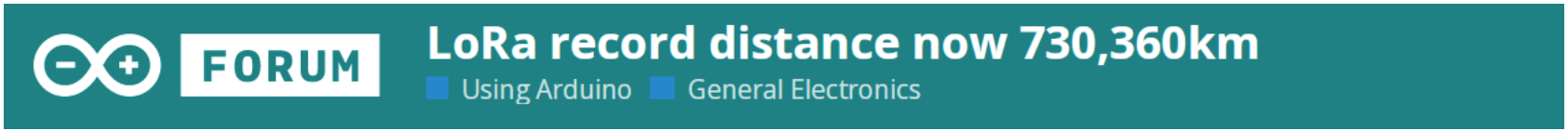
January 2021

Koppelting 2017

- 38.772 km altitude
- 702.676 km distance

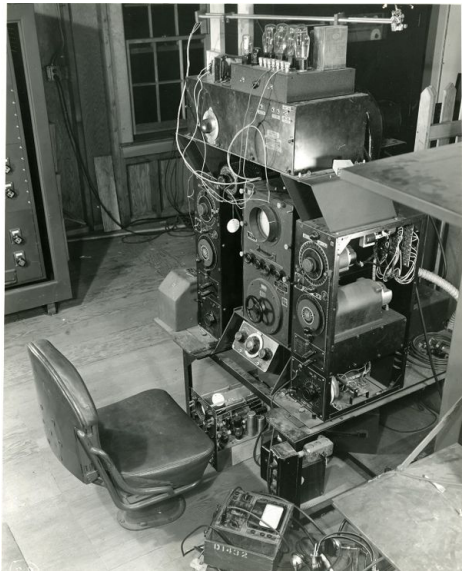


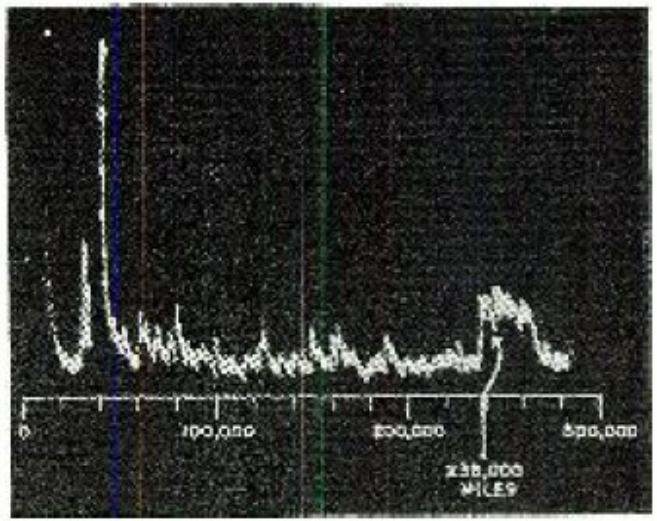
(but we also learnt a lot)



Moon Bounce

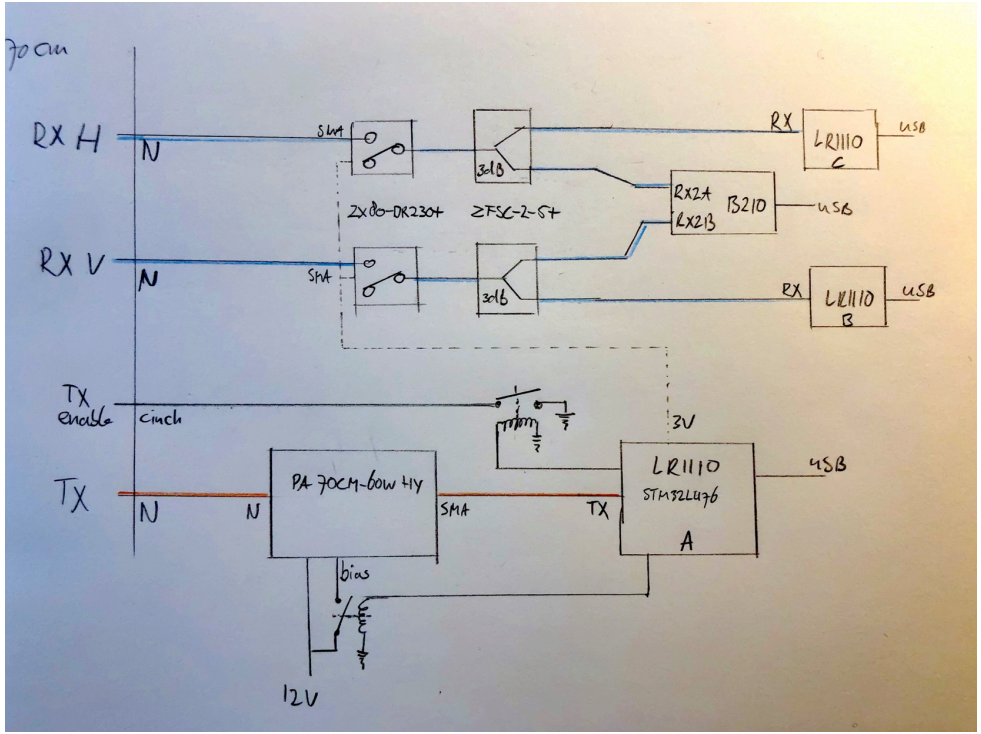
Project Diana 1946



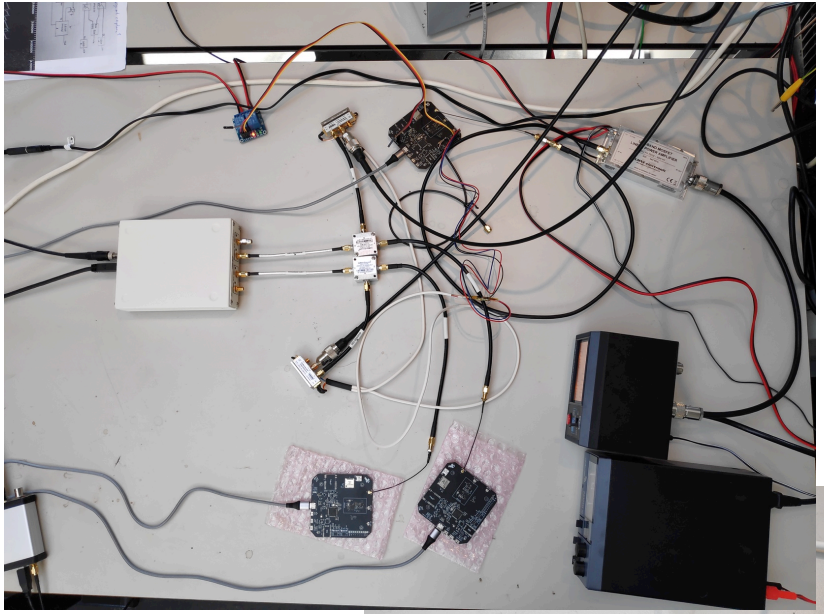


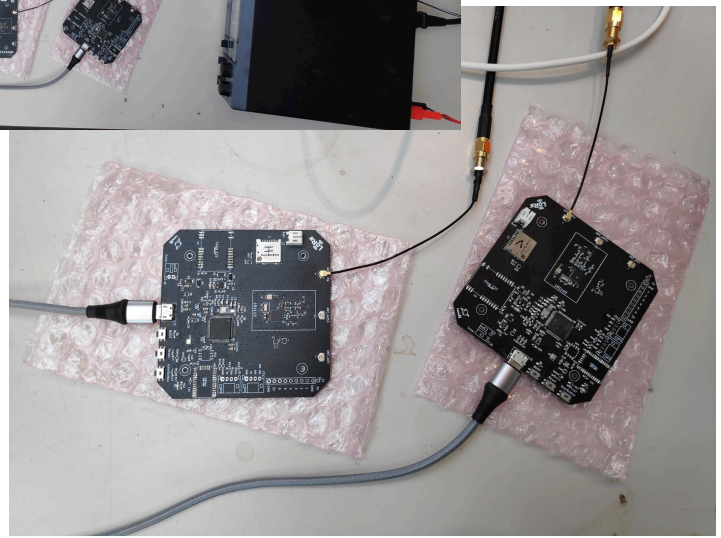
Dwingeloo Radio Telescope

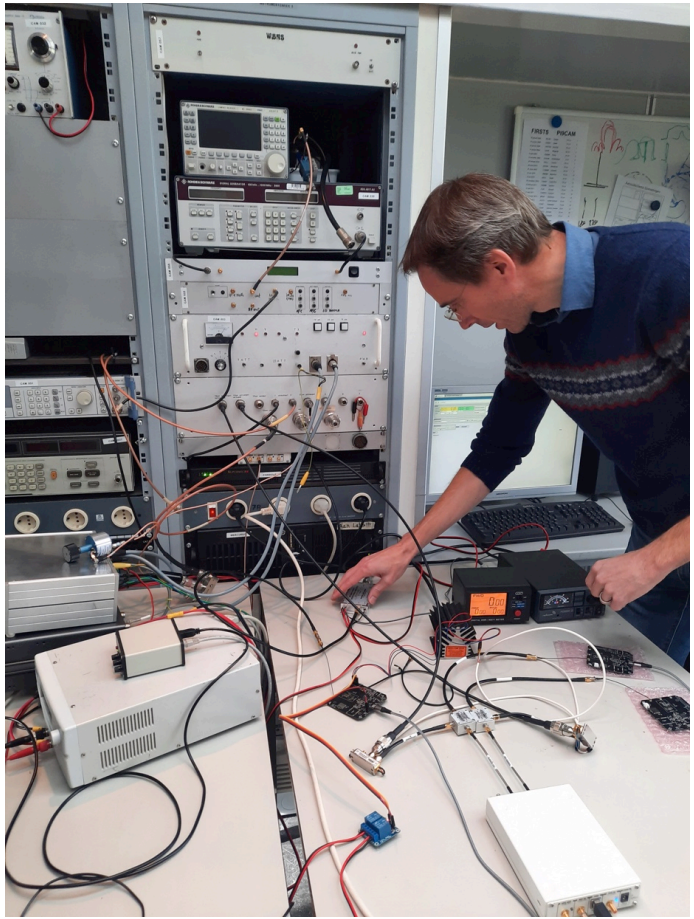
Figuur 18: C.A.Muller in waarneemkamer van de 25 meter radiotelescoop.

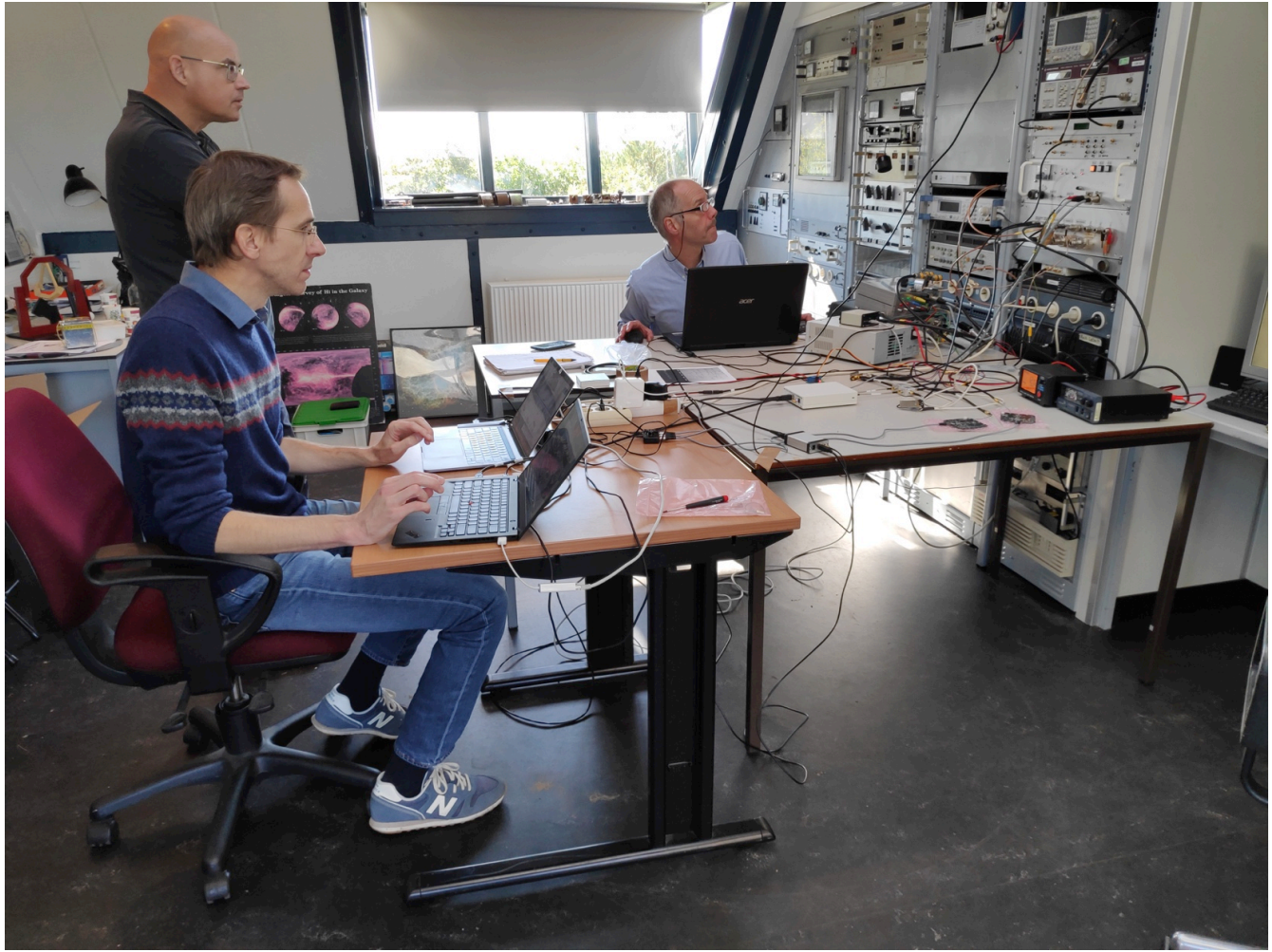


Earth-Moon-Earth 262 dB path loss
0.00000000000000000000000063 % of the signal is returned



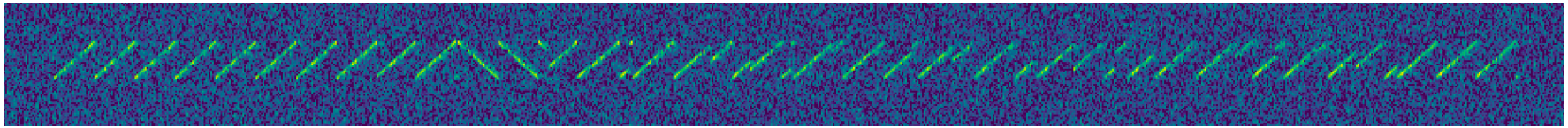




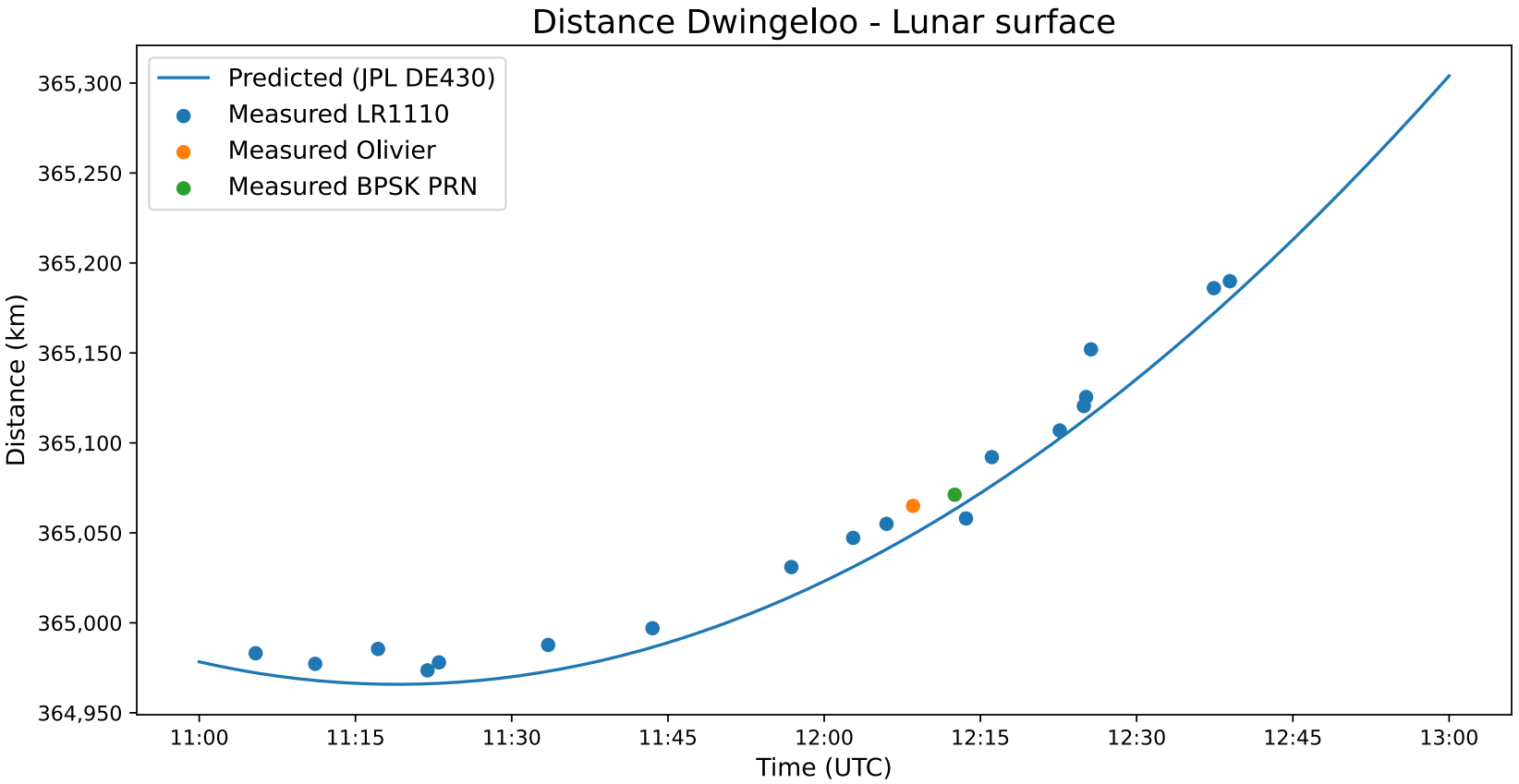


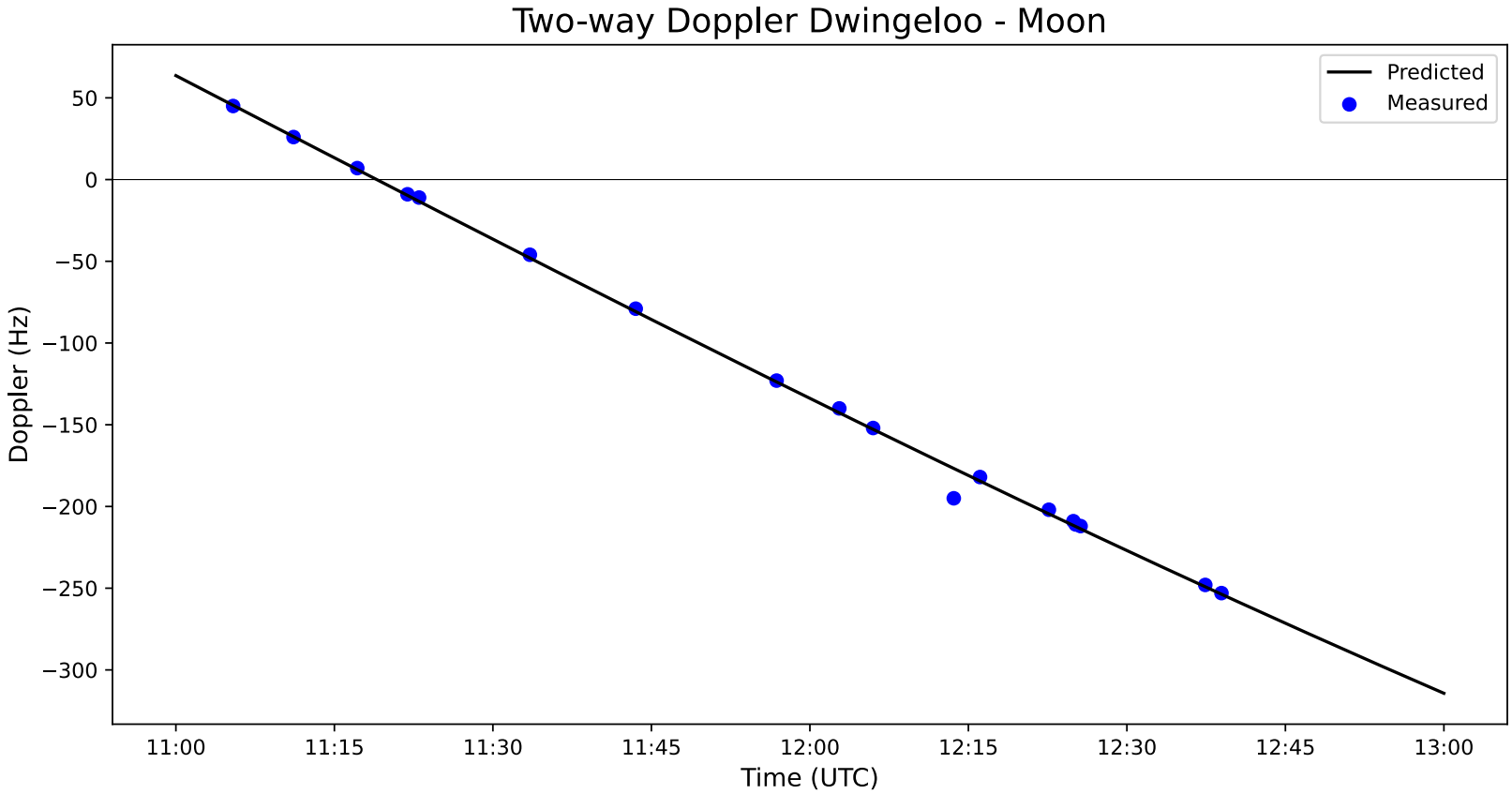
First LoRa moon bounce!

```
2021-10-05 13:05:22 ==== Waiting for RX: 6
2021-10-05 13:05:25 T: 2590926350
2021-10-05 13:05:25 DT: 2434905
2021-10-05 13:05:25 DIST: 364983.05
2021-10-05 13:05:25 CR: 4
2021-10-05 13:05:25 LoRa received
2021-10-05 13:05:25 Length: 6
2021-10-05 13:05:25 SNR: -4
2021-10-05 13:05:25 RSSI: -101
2021-10-05 13:05:25 SignalRSSI: -106
2021-10-05 13:05:25 Freq Error: -33
2021-10-05 13:05:25 Doppler: -45
2021-10-05 13:05:25 Payload: 50 49 39 43 41 4D
2021-10-05 13:05:25 P I 9 C A M
```



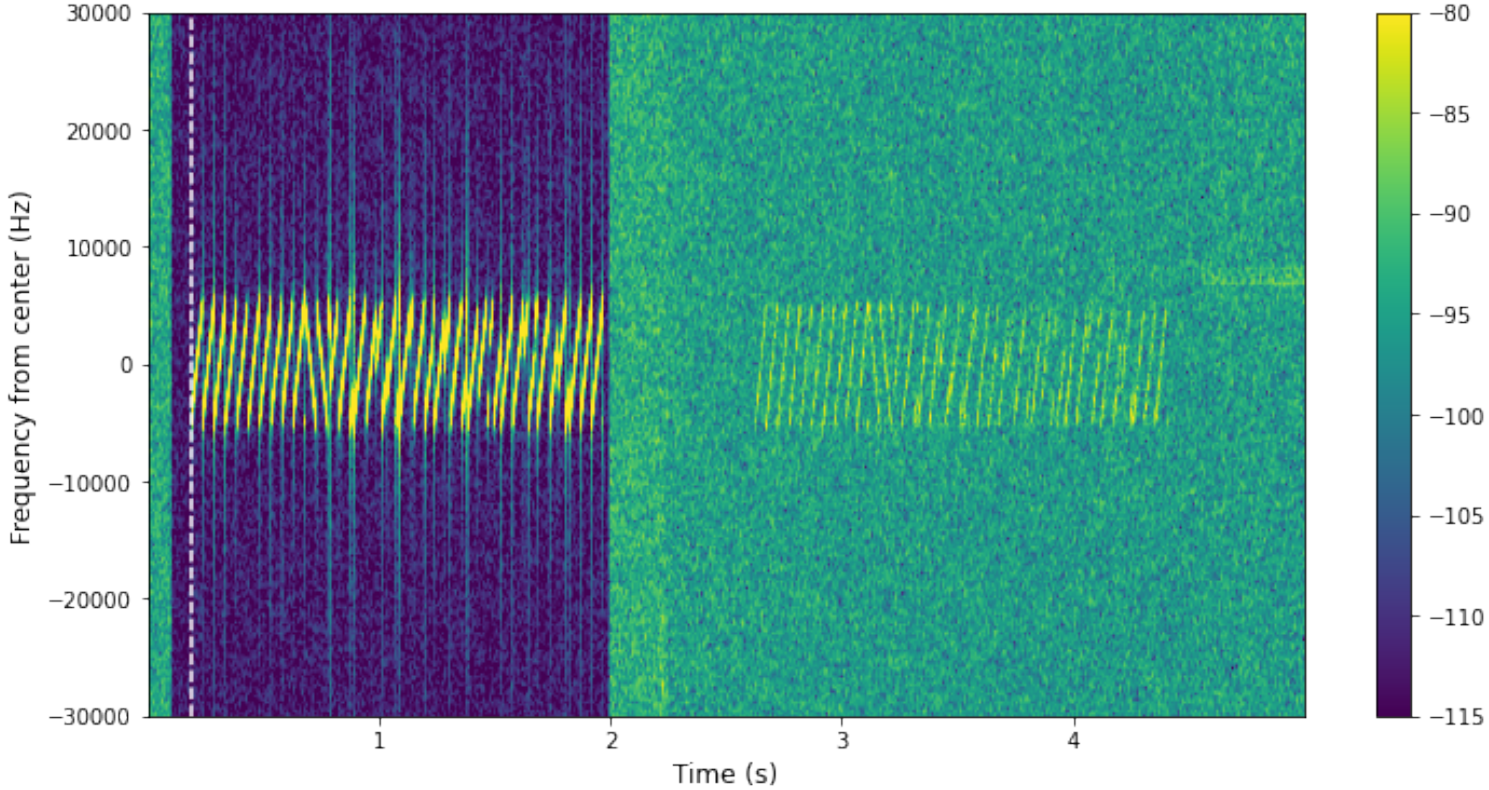
Sound!

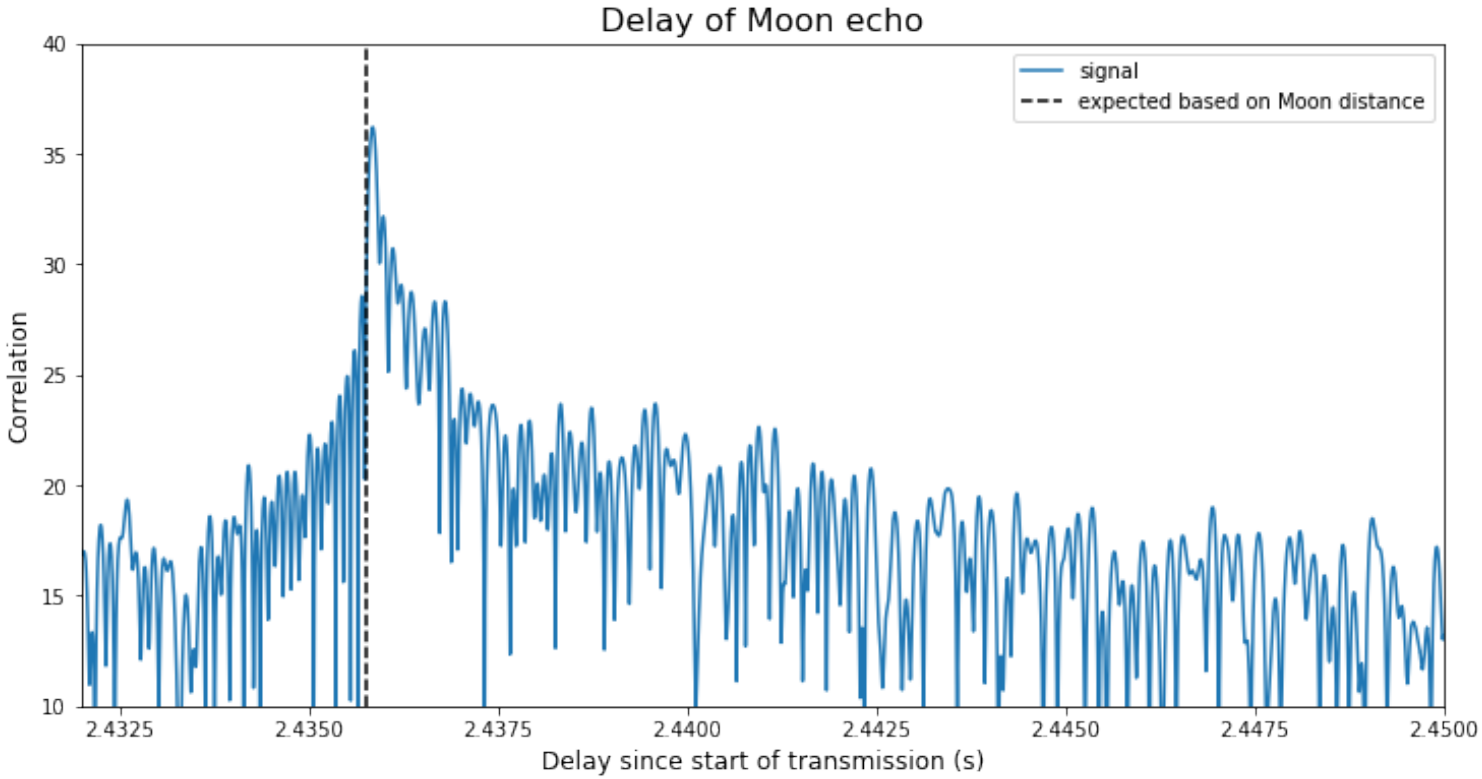

Distance Dwingeloo - Lunar surface
Predicted (JPL DE430)
Measured LR1110
Measured Olivier
Measured BPSK PRN
365,300
365,250
365,200
365,150
365,100
365,050
365,000
364,950
Distance (km)
11:00
11:15
11:30
11:45
12:00
12:15
12:30
12:45
13:00
Time (UTC)

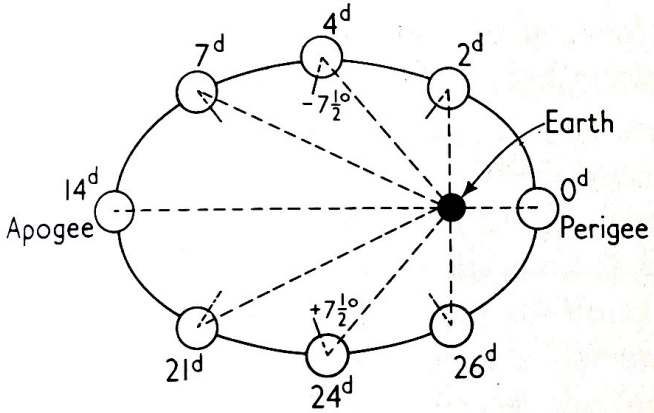

Two-way Doppler Dwingeloo - Moon
Predicted
Measured
Doppler (Hz)
50
0
−50
−100
−150
−200
−250
−300
11:00
11:15
11:30
11:45
12:00
12:15
12:30
12:45
13:00
Time (UTC)

434 Mhz

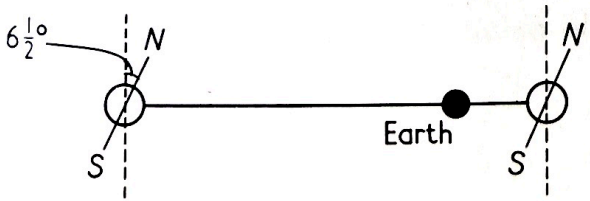
OCTOBER 5TH 2021


30000
20000
10000
0
−10000
−20000
−30000
Frequency from center (Hz)
1
2
3
4
Time (s)
−80
−85
−90
−95
−100
−105
−110
−115

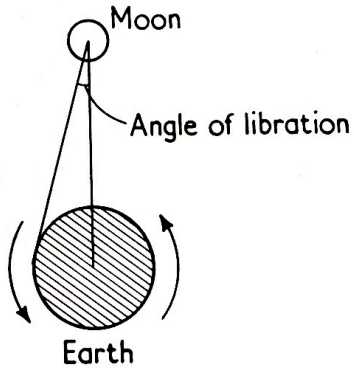

Delay of Moon echo
signal
expected based on Moon distance
Correlation
40
35
30
25
20
15
10
2.4325
2.4350
2.4375
2.4400
2.4425
2.4450
2.4475
2.4500
Delay since start of transmission (s)



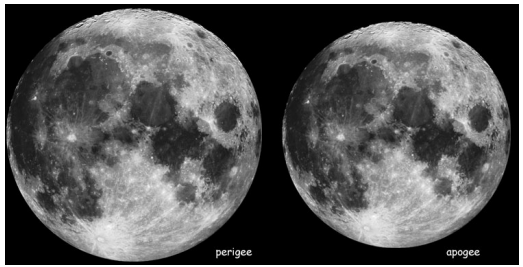
(a) Libration in longitude (plan)



(b) Libration in latitude (elevation)



(c) Diurnal libration



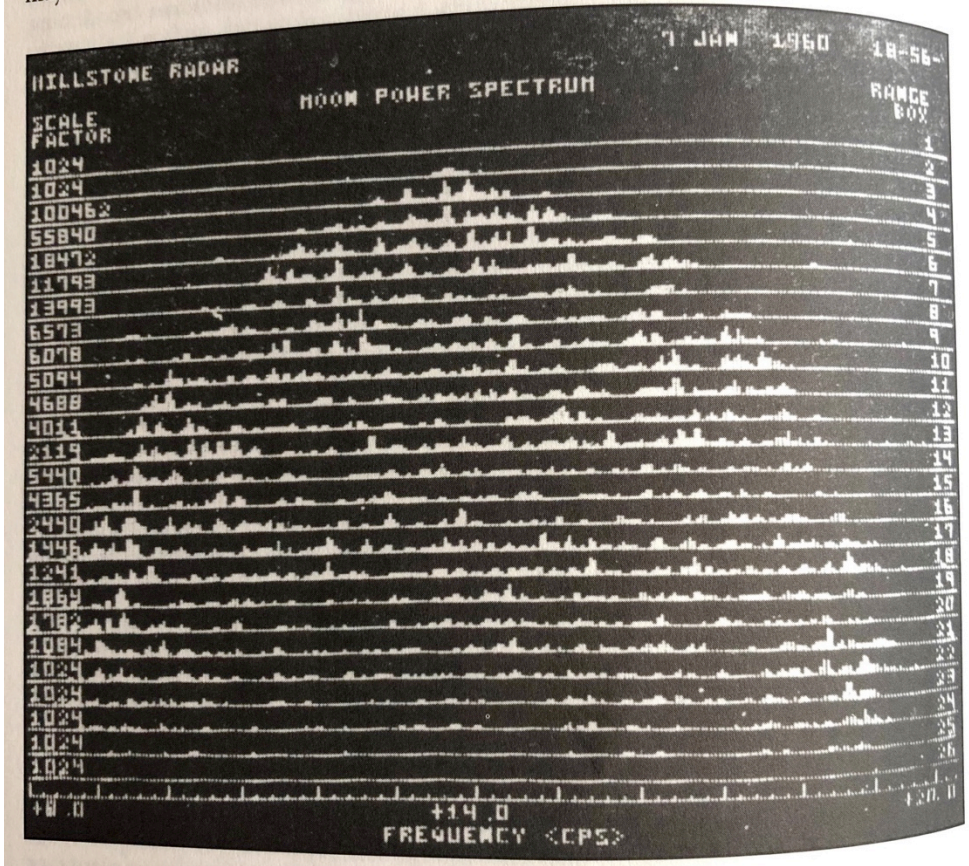
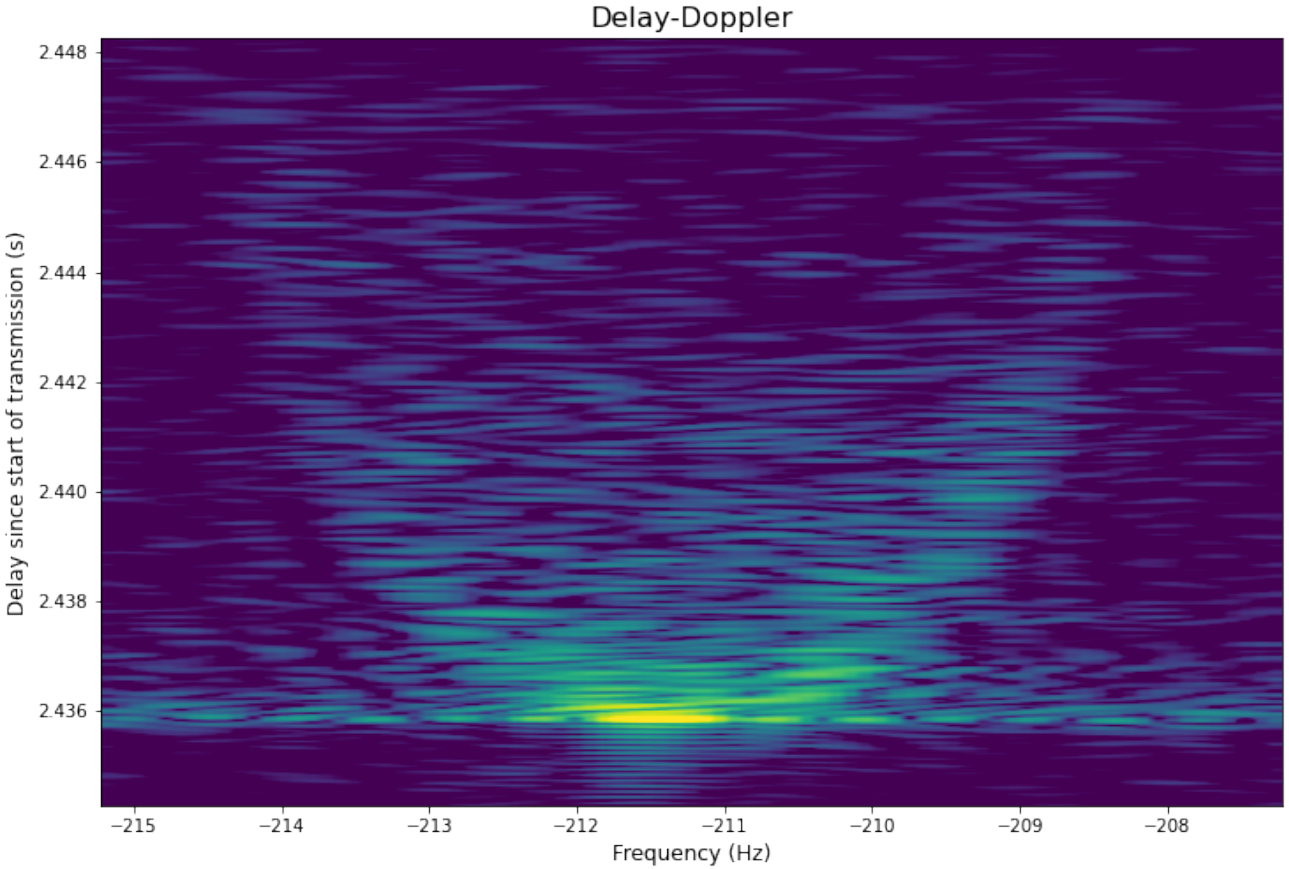


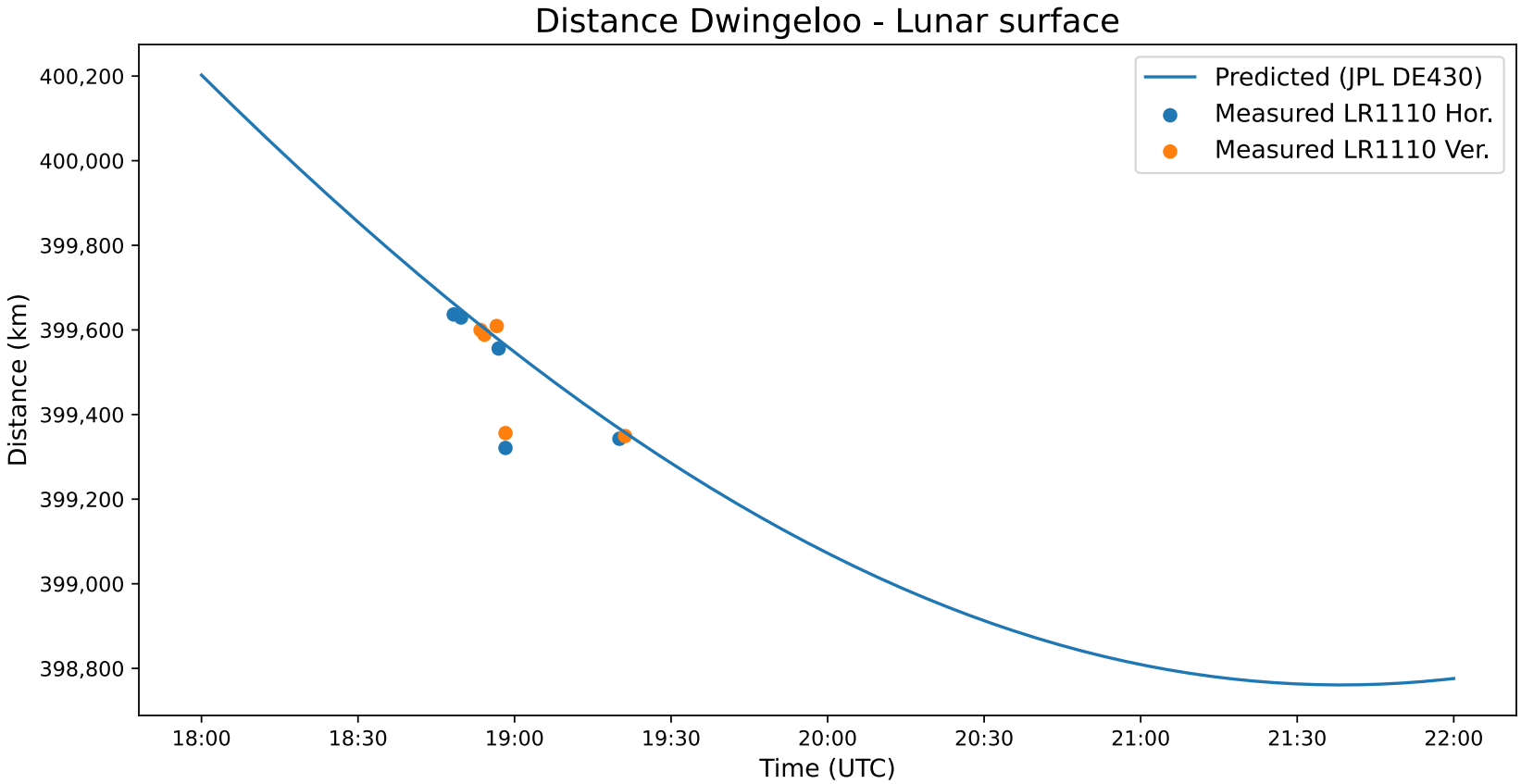
Figure 16

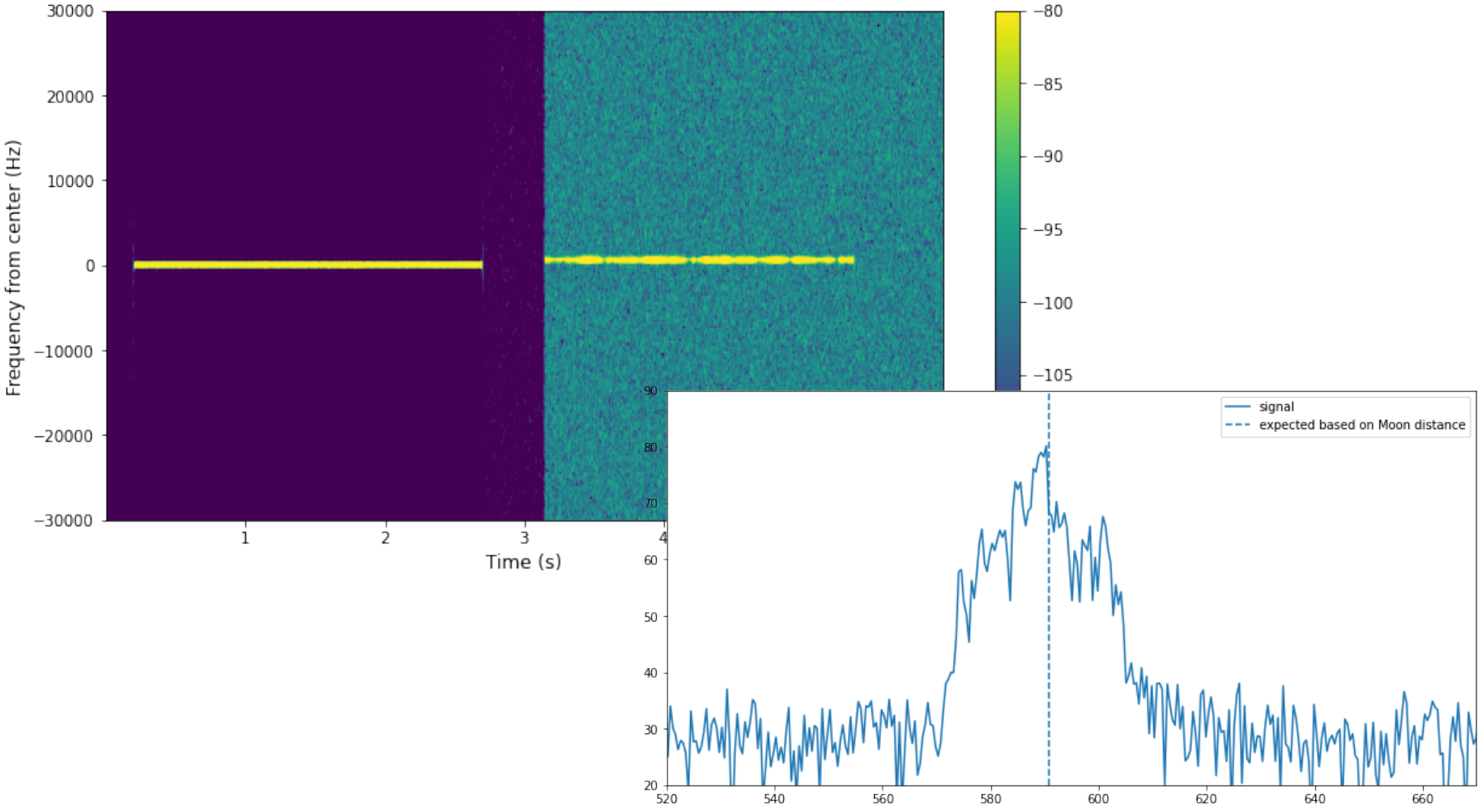
The first range-Doppler image of the Moon, 7 January 1960, made by Gordon Pettengill, using techniques developed by his Lincoln Laboratory colleague Paul Green. The top of the image (shown in range box 2) represents the point on the lunar surface closest to the radar. Pettengill, as the first associate director of the Arecibo Ionospheric Observatory, as it was then called, later guided range-Doppler imaging of the Moon and planets at Arecibo as well as at the Haystack Observatory. (Courtesy of MIT Lincoln Laboratory, Lexington, Massachusetts, photo no. 261209-1D.)

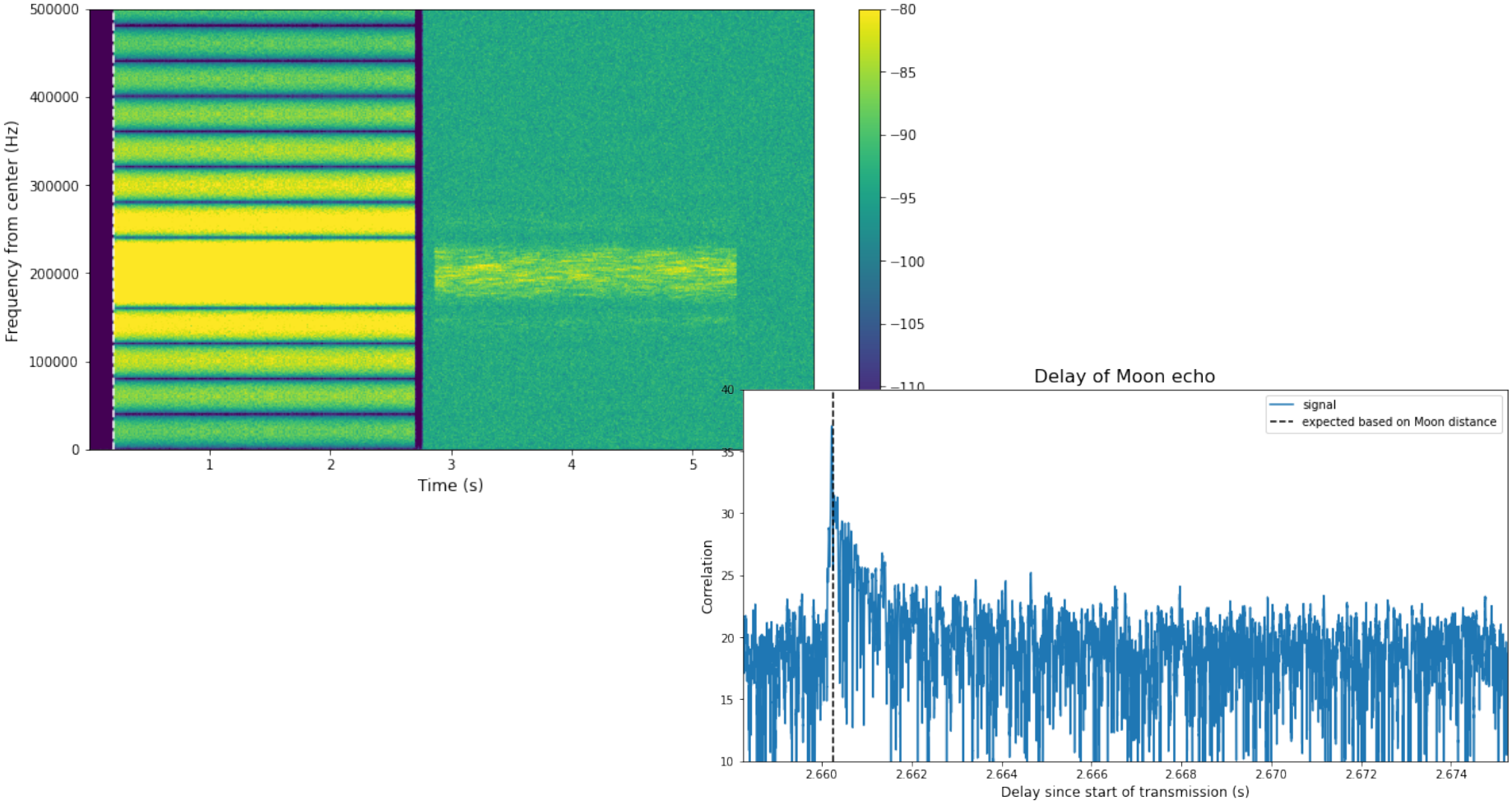

Delay-Doppler
Delay since start of transmission (s)
2.448
2.446
2.444
2.442
2.440
2.438
2.436
−215
−214
−213
−212
−211
−210
−209
−208
Frequency (Hz)

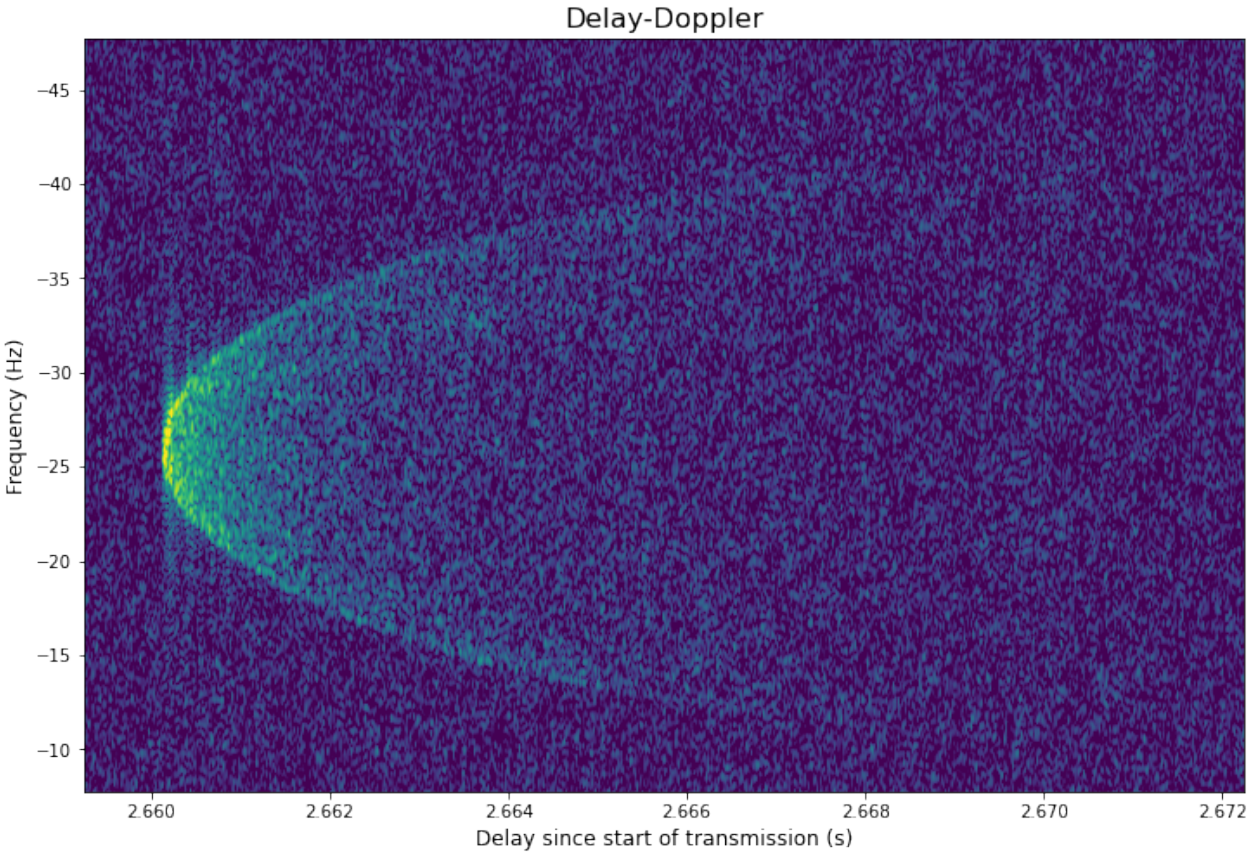
1297 Mhz

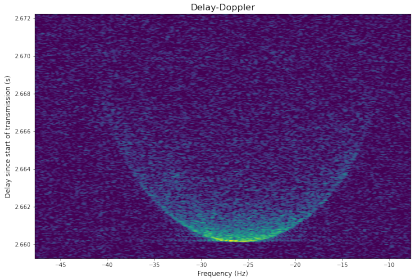
DECEMBER 16TH 2021

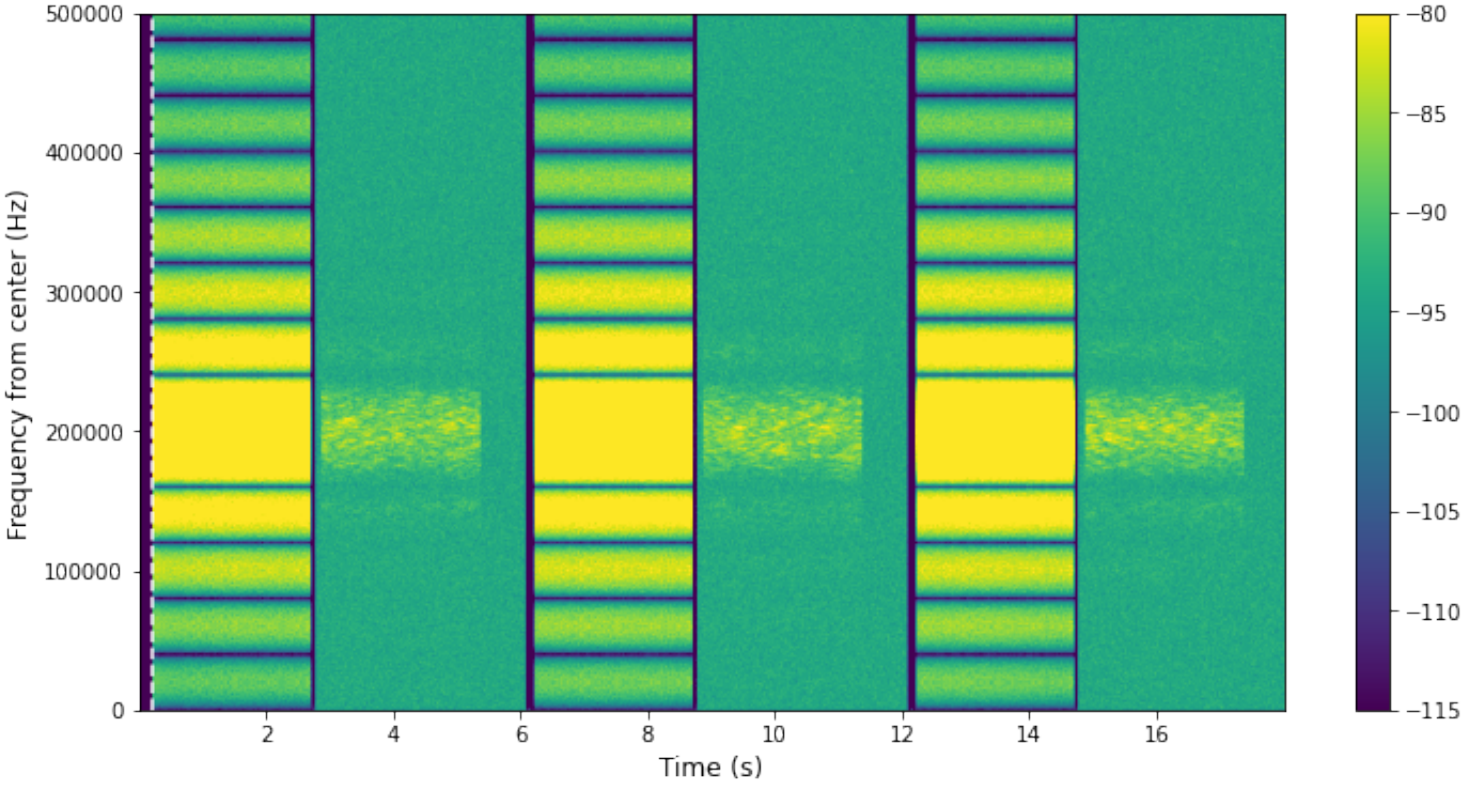

Distance Dwingeloo - Lunar surface
Predicted (JPL DE430)
Measured LR1110 Hor.
Measured LR1110 Ver.
Distance (km)
400,200
400,000
399,800
399,600
399,400
399,200
399,000
398,800
18:00
18:30
19:00
19:30
20:00
20:30
21:00
21:30
22:00
Time (UTC)

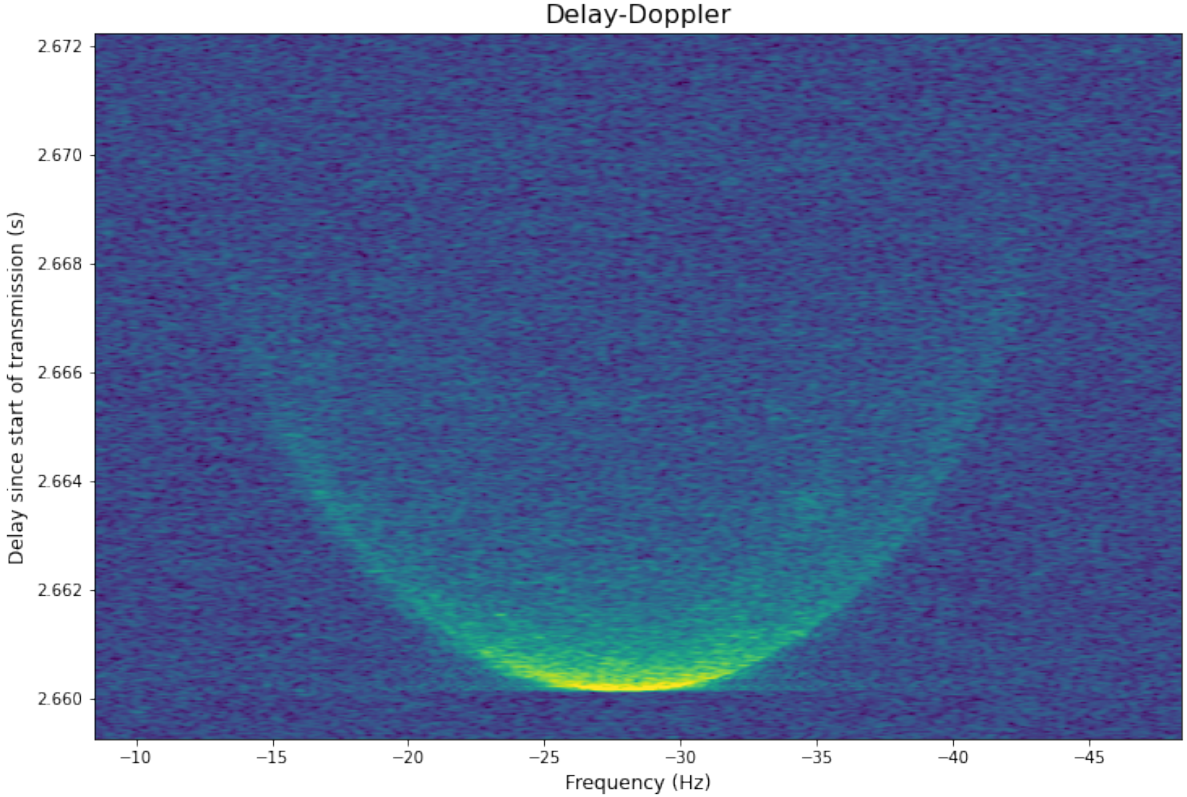

Frequency from center (Hz)
30000
20000
10000
0
−10000
−20000
−30000
1
2
3
Time (s)
−80
−85
−90
−95
−100
−105
90
80
70
60
50
40
30
20
520
540
560
580
600
620
640
660
signal
expected based on Moon distance


Frequency from center (Hz)
500000
400000
300000
200000
100000
0
1
2
3
4
5
Time (s)
−80
−85
−90
−95
−100
−105
−110
Delay of Moon echo
signal
expected based on Moon distance
Correlation
40
35
30
25
20
15
10
2.660
2.662
2.664
2.666
2.668
2.670
2.672
2.674
Delay since start of transmission (s)


Delay-Doppler
Frequency (Hz)
−45
−40
−35
−30
−25
−20
−15
−10
2.660
2.662
2.664
2.666
2.668
2.670
2.672
Delay since start of transmission (s)

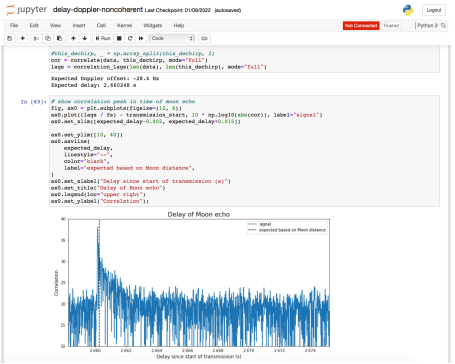

Delay-Doppler
Delay since start of transmission (s)
Frequency (Hz)

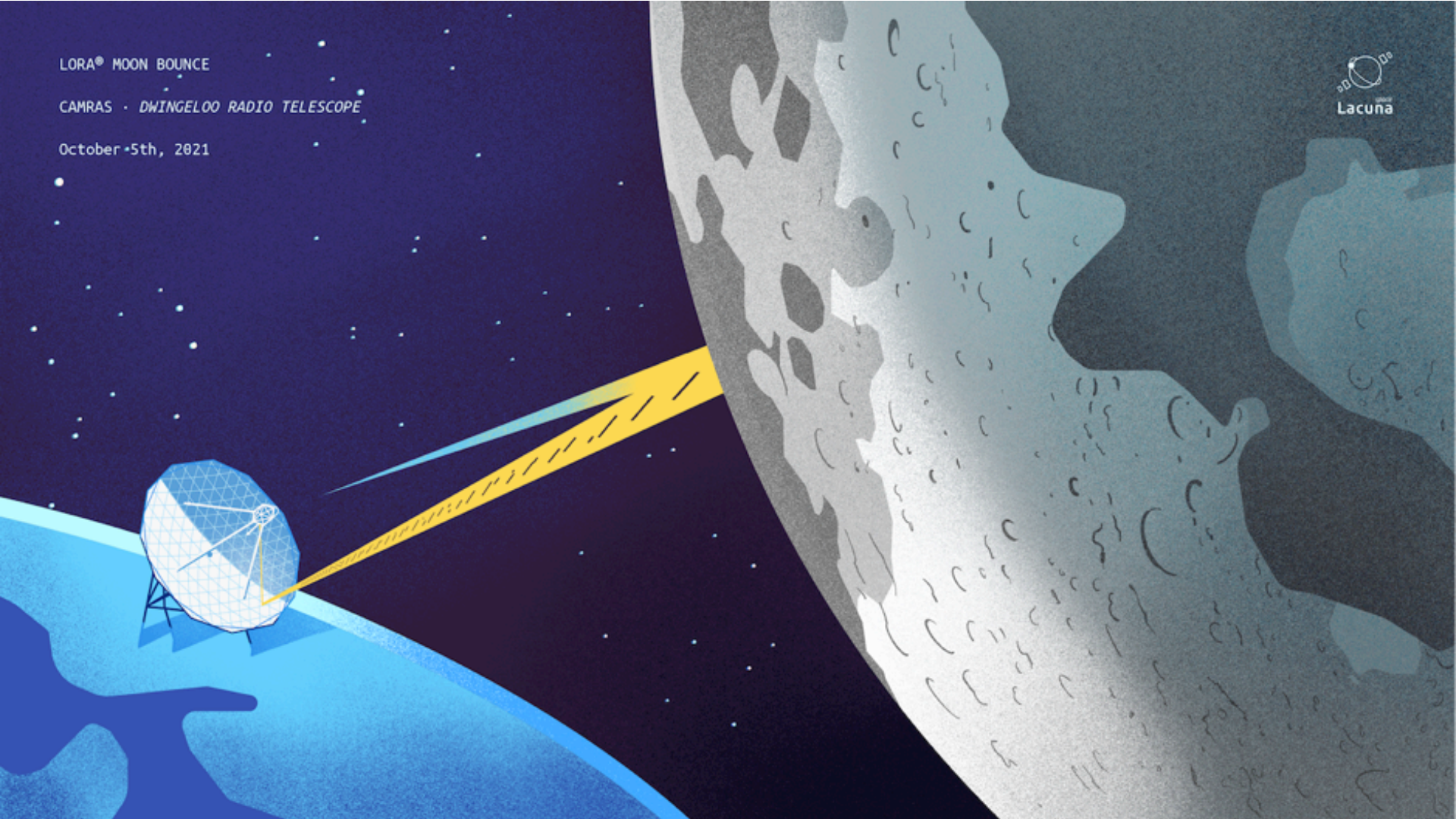

500000
400000
300000
200000
100000
0
Frequency from center (Hz)
2
4
6
8
10
12
14
16
Time (s)
−80
−85
−90
−95
−100
−105
−110
−115


Delay-Doppler
Delay since start of transmission (s)
2.672
2.670
2.668
2.666
2.664
2.662
2.660
−10
−15
−20
−25
−30
−35
−40
−45
Frequency (Hz)

Work In Progress

- Publish data on Zenodo (IQ in SigMF)
  - https://zenodo.org/
  - DOI Oct. 5th dataset: 10.5281/zenodo.5832579
- Publish Juypter notebooks on GitHub
- More analysis
- Applicability to moon communications?




LORA® MOON BOUNCE
CAMRAS · DWINGELOO RADIO TELESCOPE
October 5th, 2021
Lacuna