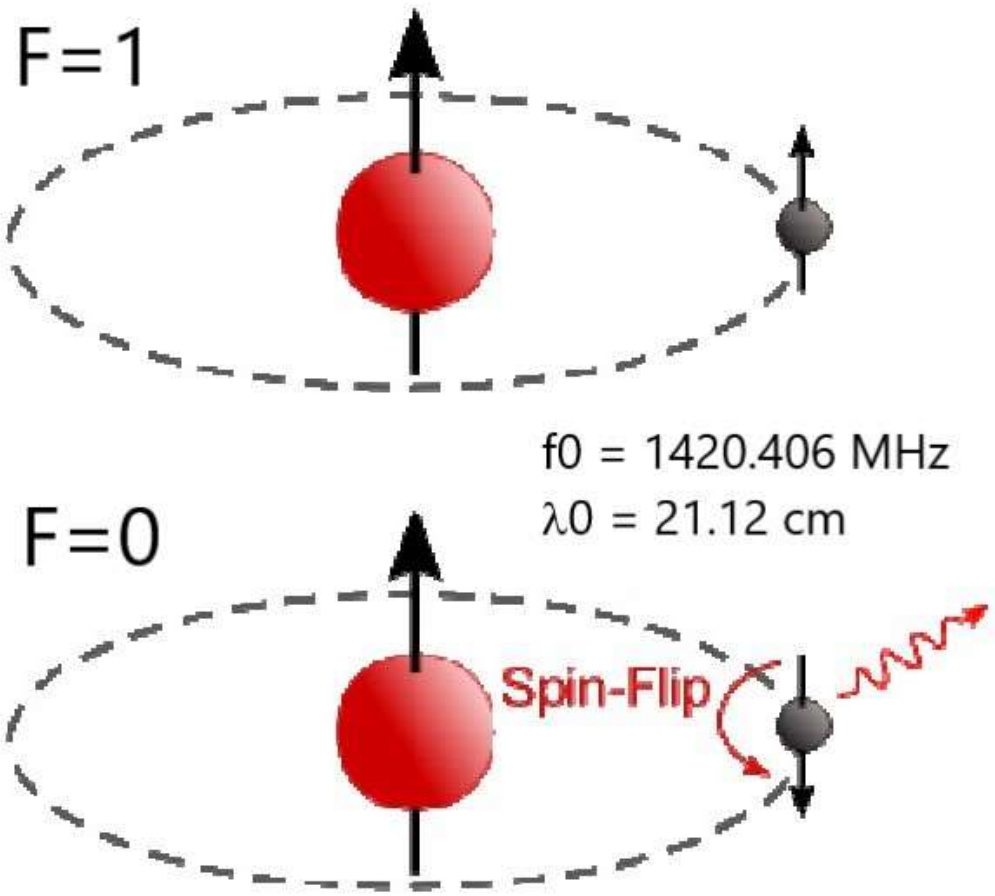
How to Observe Hydrogen Line Spectra of Galaxies Outside of the Milky Way

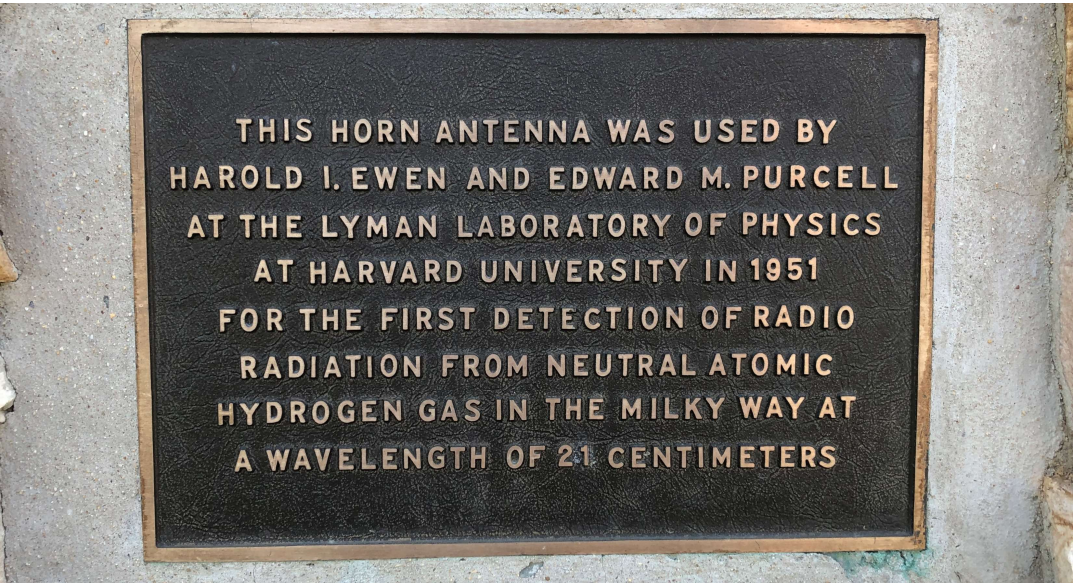
By Jason Burnfield

24 September 2024

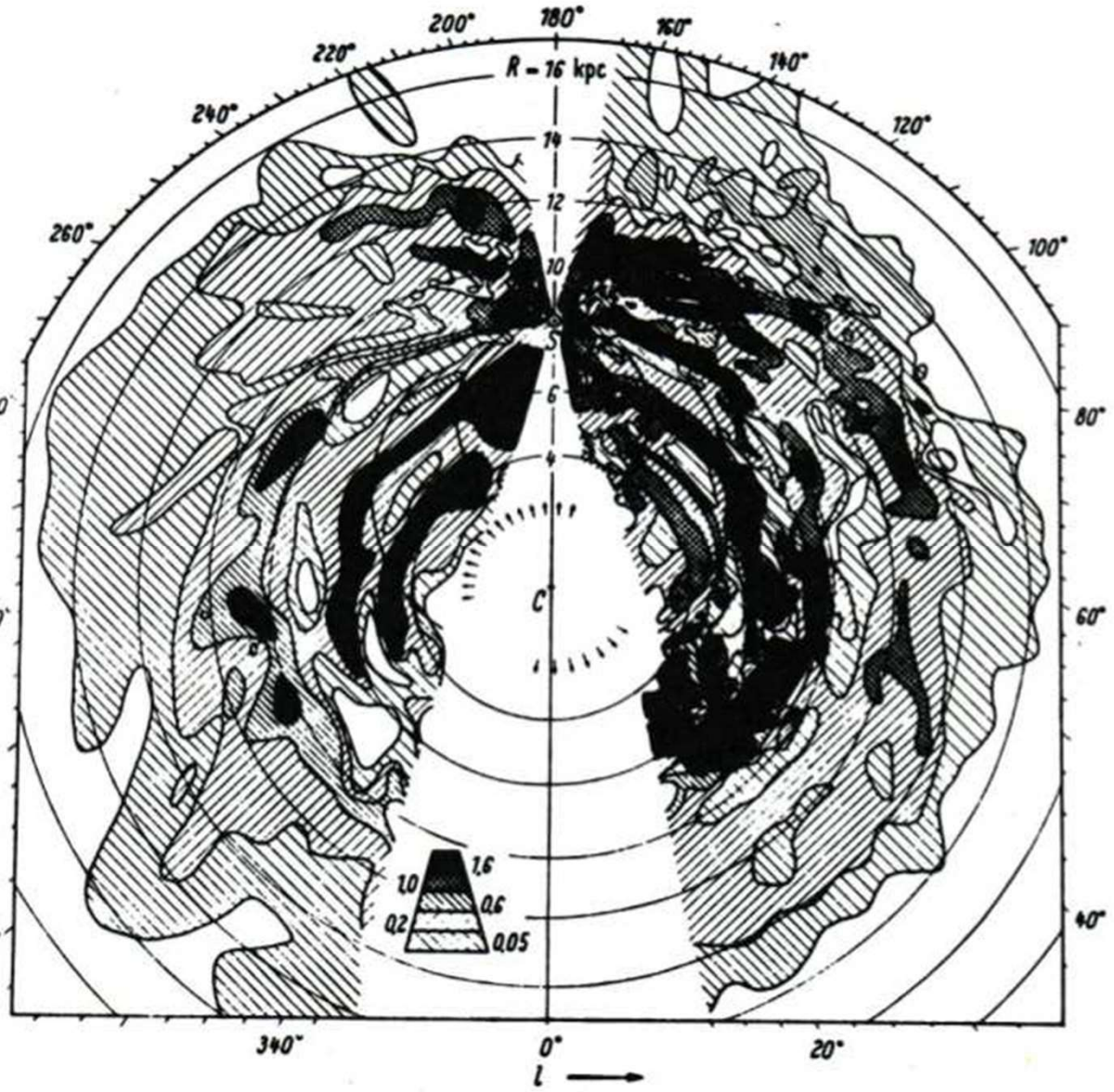
A Brief Introduction to the Hydrogen Line

The hydrogen line is an emission line of neutral atomic hydrogen caused by a "spin flip" of the electron in the ground state.



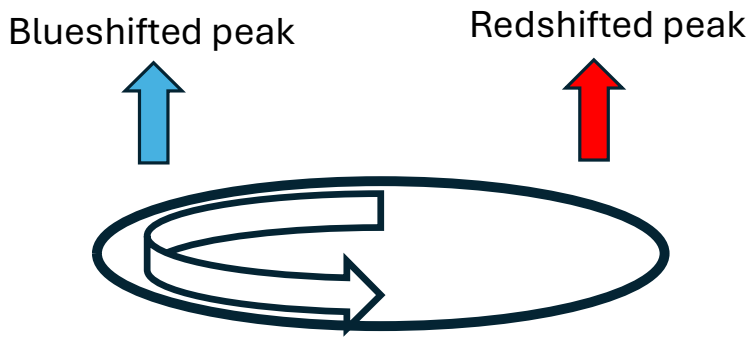


The hydrogen line was first observed in 1951 by Harold Ewen and Edward Purcell at Harvard University using the horn antenna shown here.

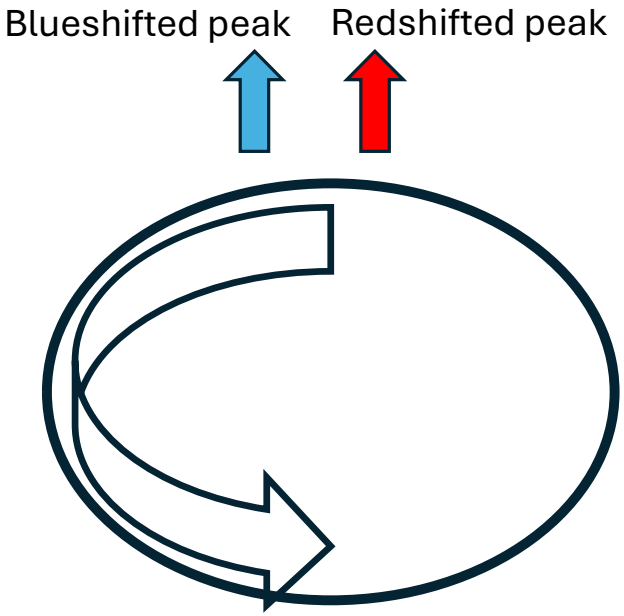


- Map of neutral atomic hydrogen (21- cm line) published by Jan Oort (1958); figure taken from the text book Scheffler & Elsässer (1992). The Sun is in the upper part of the plot at 8 kpc.
- This was produced using the doppler shift observed in 21 cm emissions along various lines of sight within the galactic plane.
- The reason for the “blind spots’ toward and away from the center of the galaxy are due to geometry. For angles close to 180 or 0 degrees, the relative motion is entirely tangential and there is no doppler shift.

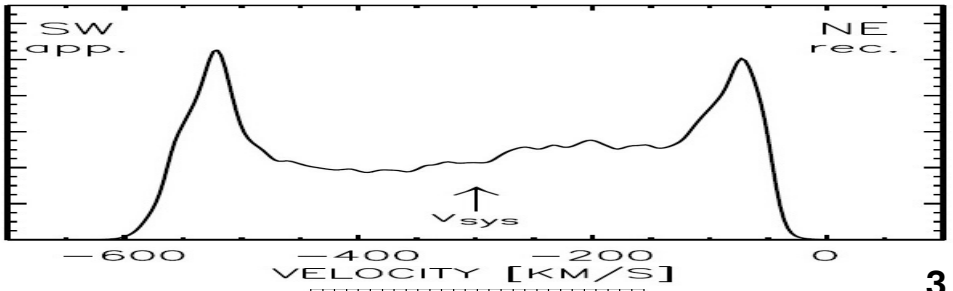
When observing hydrogen spectra from spiral galaxies outside the milky way, the single hydrogen peak gets split in two by doppler shift due to the spinning motion of the disc.



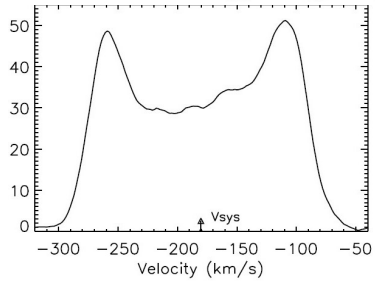
The distance between the peaks indicates the orientation of the disc from our vantage point.



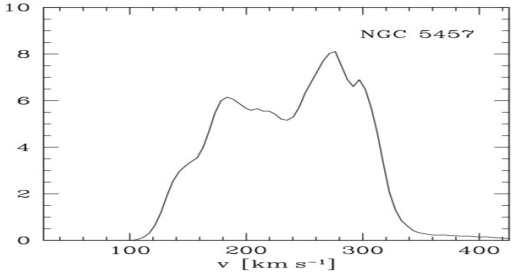
The more “edge-on” the further apart the peaks, the more “ face-on” the closer to together they are.


SW
app.
NE
rec.
Vsys
−600
−400
−200
0
VELOCITY [KM/S]

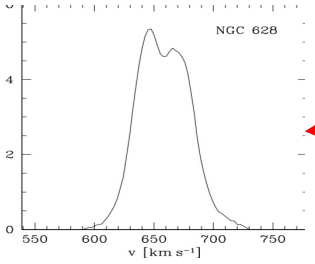
3


50
40
30
20
10
0
Vsys
−300 −250 −200 −150 −100 −50
Velocity (km/s)

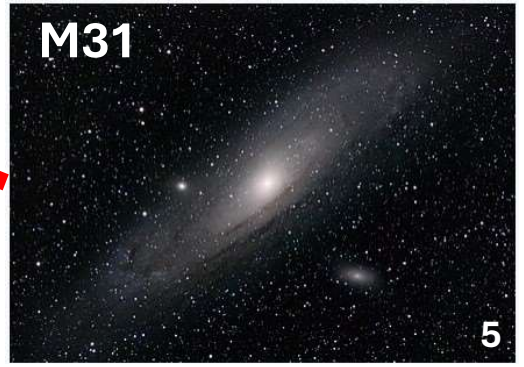
4


NGC 5457
10
8
6
4
2
0
100
200
300
400
v [km s⁻¹]

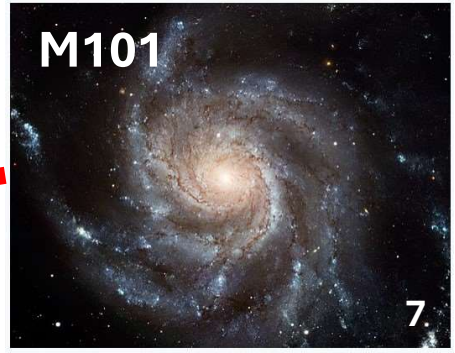
2

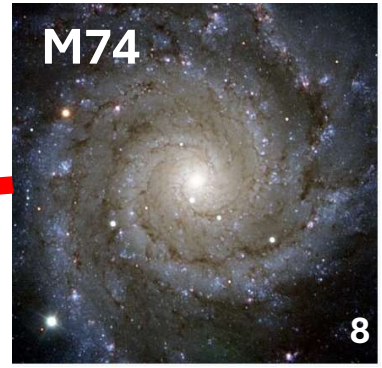

NGC 628
4
2
0
550
600
650
700
750
v [km s⁻¹]

2


M31
5

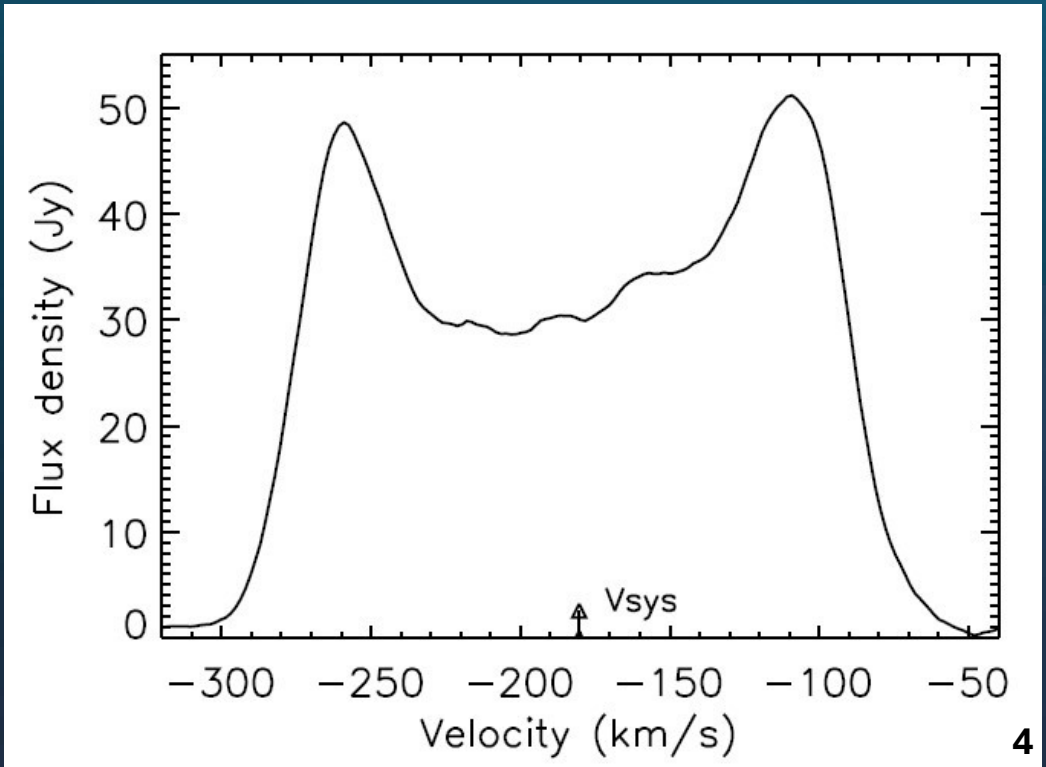

M33
6


M101
7


M74
8

Drift Scanning with a Small Dish
(I suggest at least 2.5 meters or larger)

Planning Your Observation

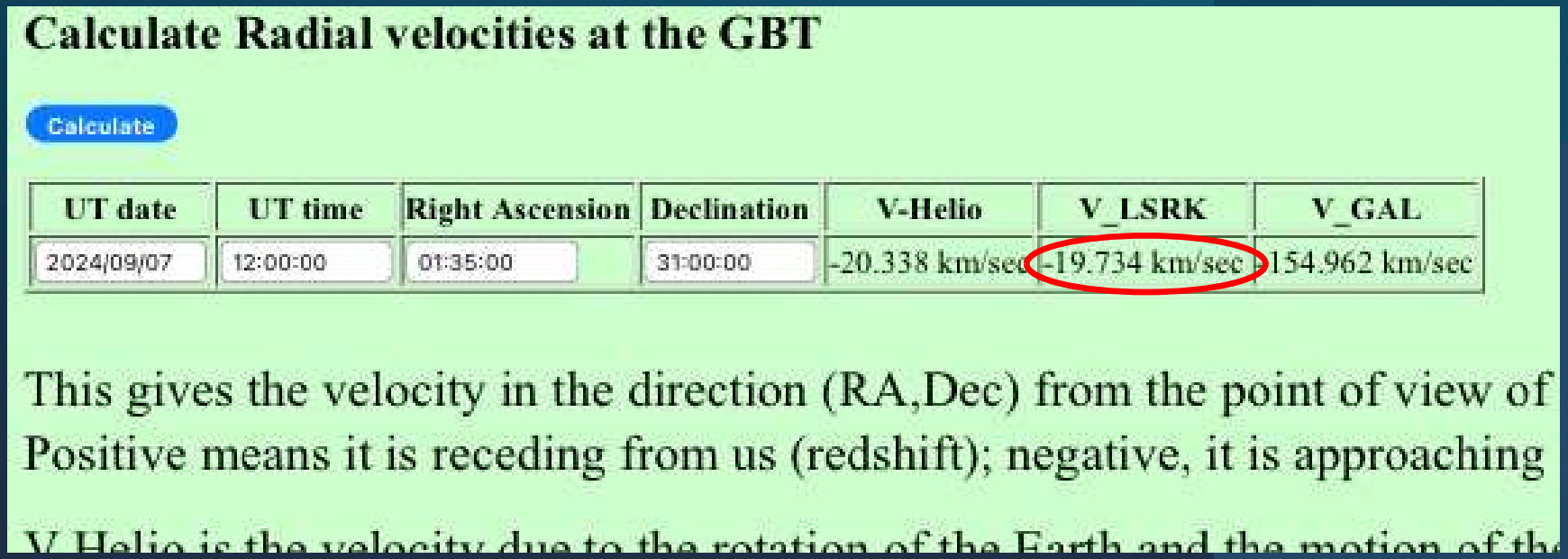


4

Observation data (J2000 epoch)	
Pronunciation	/traɪˈæŋgjʊləm/
Constellation	Triangulum
Right ascension	$01^h\ 33^m\ 50.02^s$[1]
Declination	+30° 39′ 36.7″[1]
Redshift	-0.000607 ± 0.000010[1]
Heliocentric radial velocity	-179 ± 3 km/s[2]
Galactocentric velocity	-44 ± 6 km/s[2]
Distance	970 kpc (3.2 Mly)[3]
Apparent magnitude (V)	5.72[1]

6

Gather information on your target galaxy from credible sources (including RA/Dec coordinates, reference profile, and/or average radial velocity).



Calculate Radial velocities at the GBT

Calculate

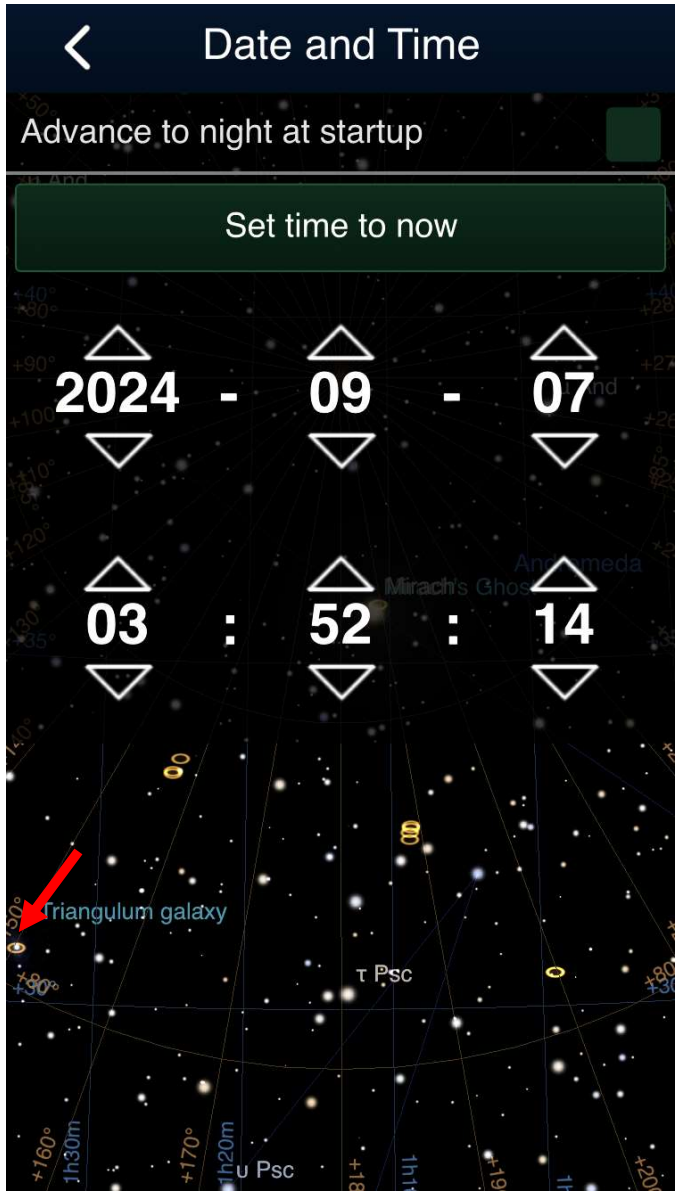
UT date	UT time	Right Ascension	Declination	V-Helio	V_LSRK	V_GAL
2024/09/07	12:00:00	01:35:00	31:00:00	-20.338 km/sec	-19.734 km/sec	154.962 km/sec

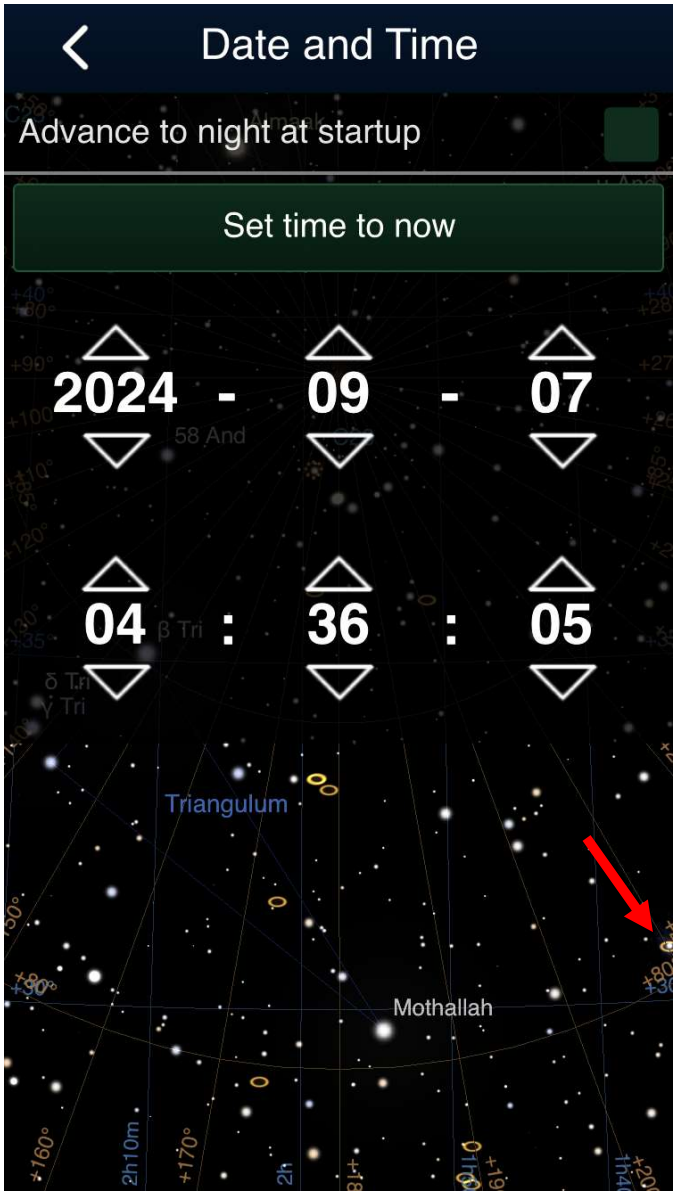
This gives the velocity in the direction (RA,Dec) from the point of view of
Positive means it is receding from us (redshift); negative, it is approaching

V_Helio is the velocity due to the rotation of the Earth and the motion of th

Look up the VLSR correction for the target galaxy coordinates on the observation date (see references at the end of this presentation for the url for this site).

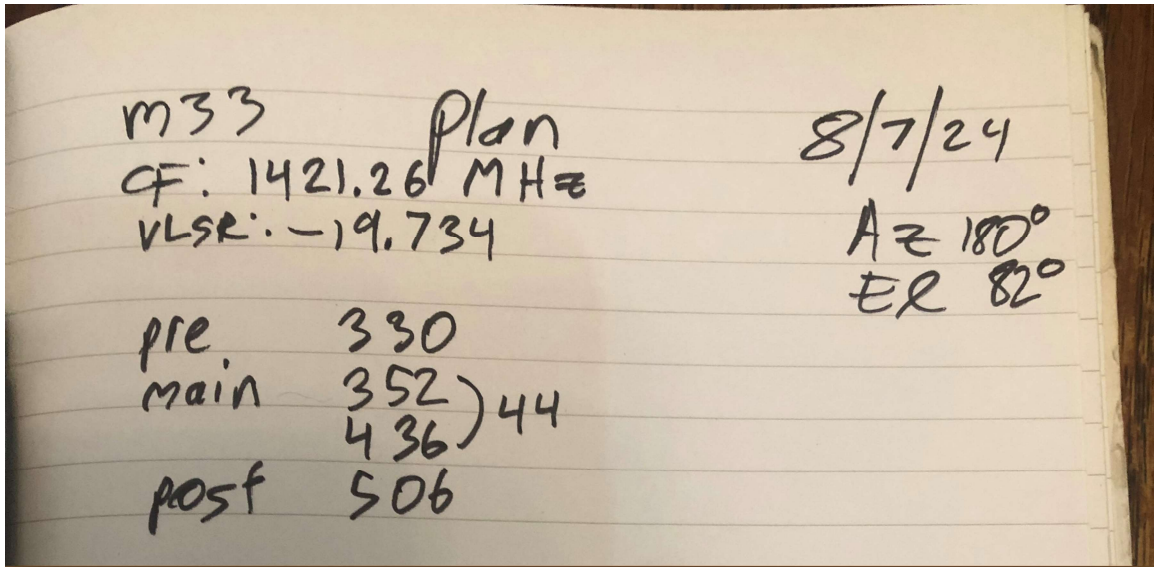
Use the Stellarium phone app to identify the start and end times of the main transit by setting the field of view equal to the HPBW of your dish and incrementing the clock until the galaxy just enters and exits the screen.





Choose a pre-transit start time and post-transit end time such that each is half the length of the main transit duration.

Select a center frequency that corresponds to the average velocity of the galaxy you want to observe.



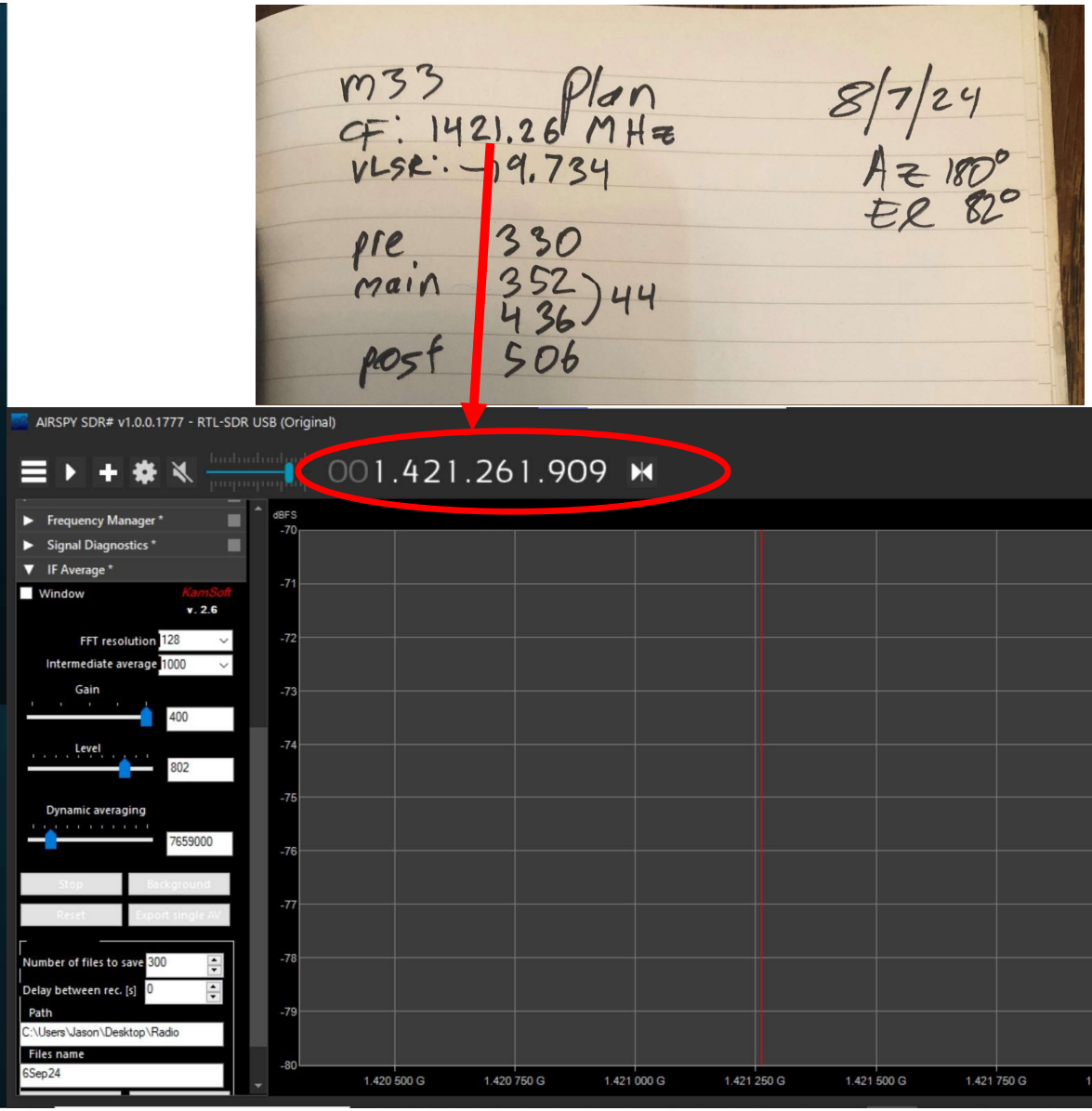
$$Fo = Fs\left[\frac{1}{(1 + V/C)}\right] = 1420.406\left[\frac{1}{(1 - 180/300{,}000)}\right]$$

$$Fo = 1421.26\ MHz$$

Collecting Observation Data

Set up your dish with the proper Azimuth/Elevation setting to do a transit scan of the target galaxy.

Set the center frequency of Airspy SDR# software to the center frequency that is recorded in your observation plan.

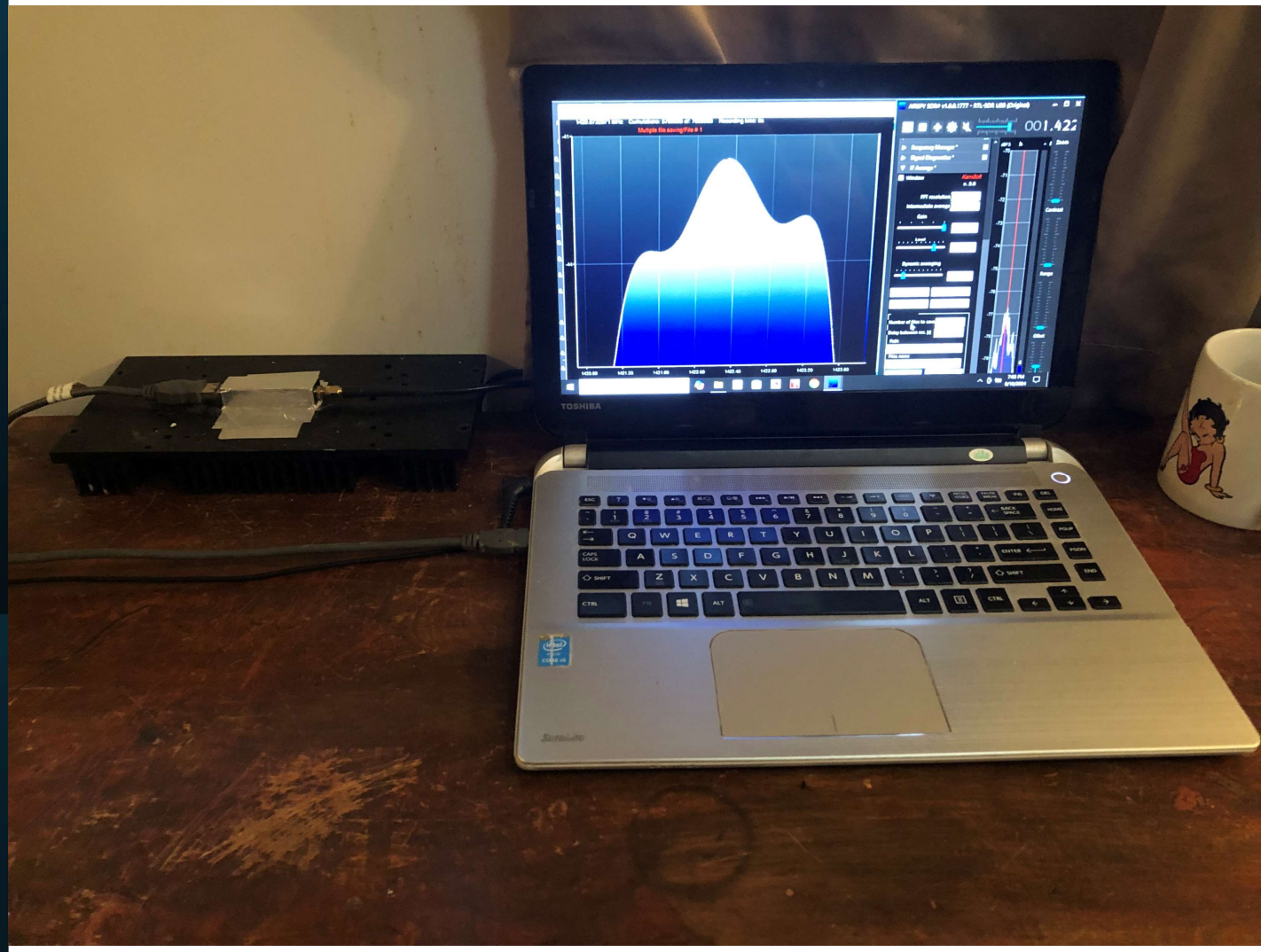


I recommend using the following settings for IF Averaging:

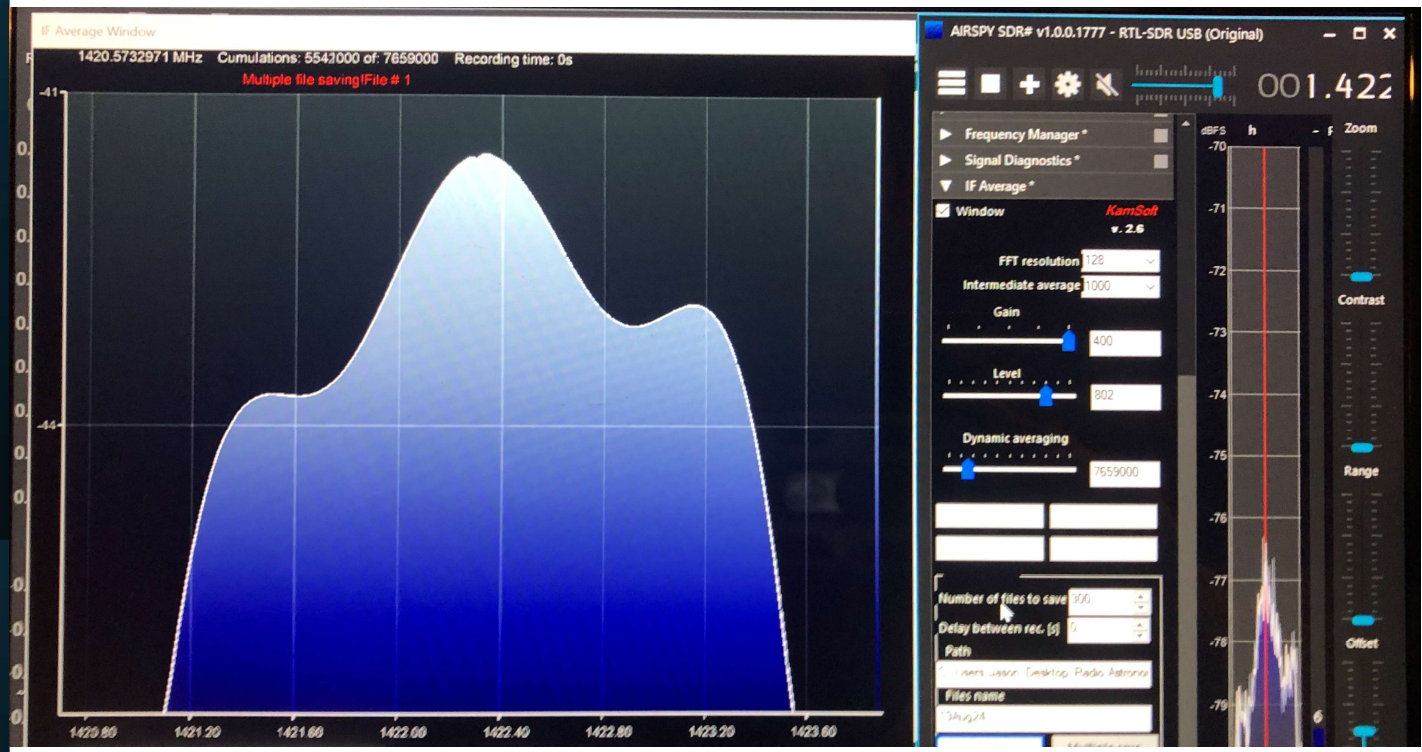
- FFT Resolution 128
- Intermediate Averaging 1000
- Dynamic Averaging 7659000

Set the default filename and path to suit your needs.

Connect your SDR, feed, LNA and Band-Pass Filter and then press “play” on SDR# to begin recording data.

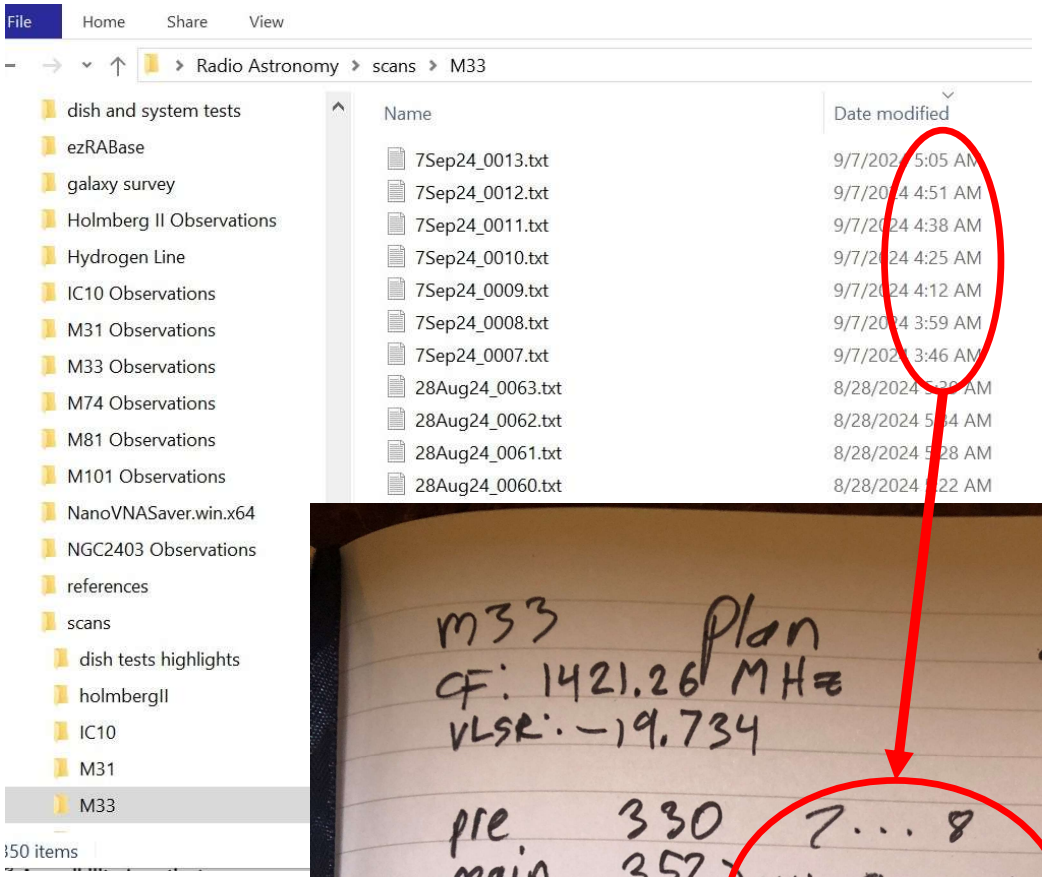


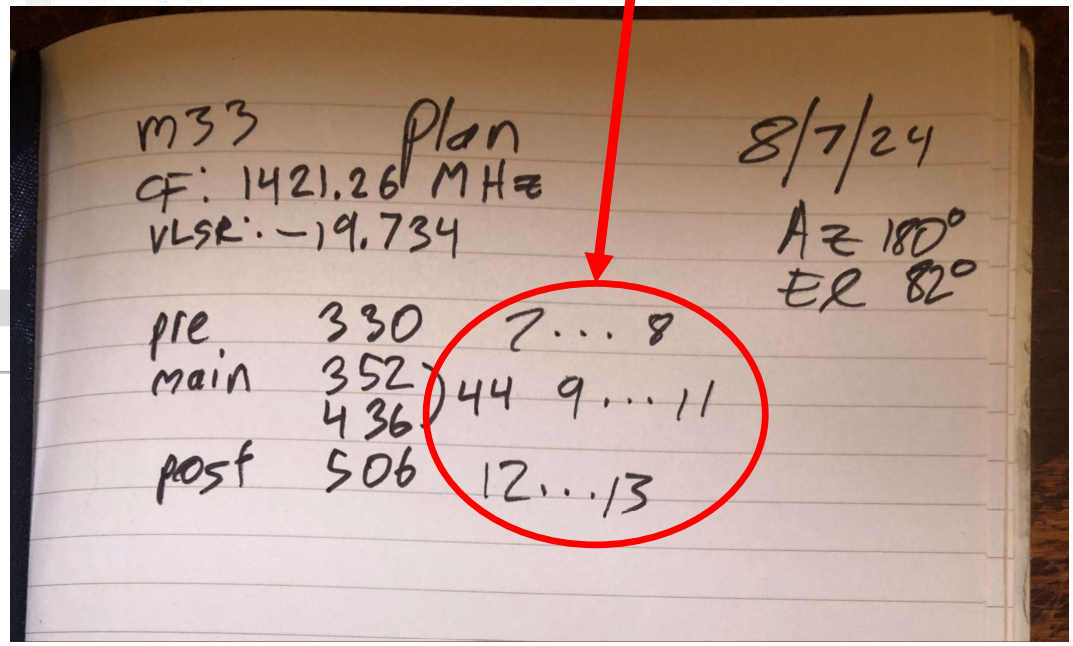
Launch IF Averaging and enable “Multiple Save”. Make sure you start at least 30 minutes before your pre-transit start time to allow the system to stabilize before collecting meaningful data.



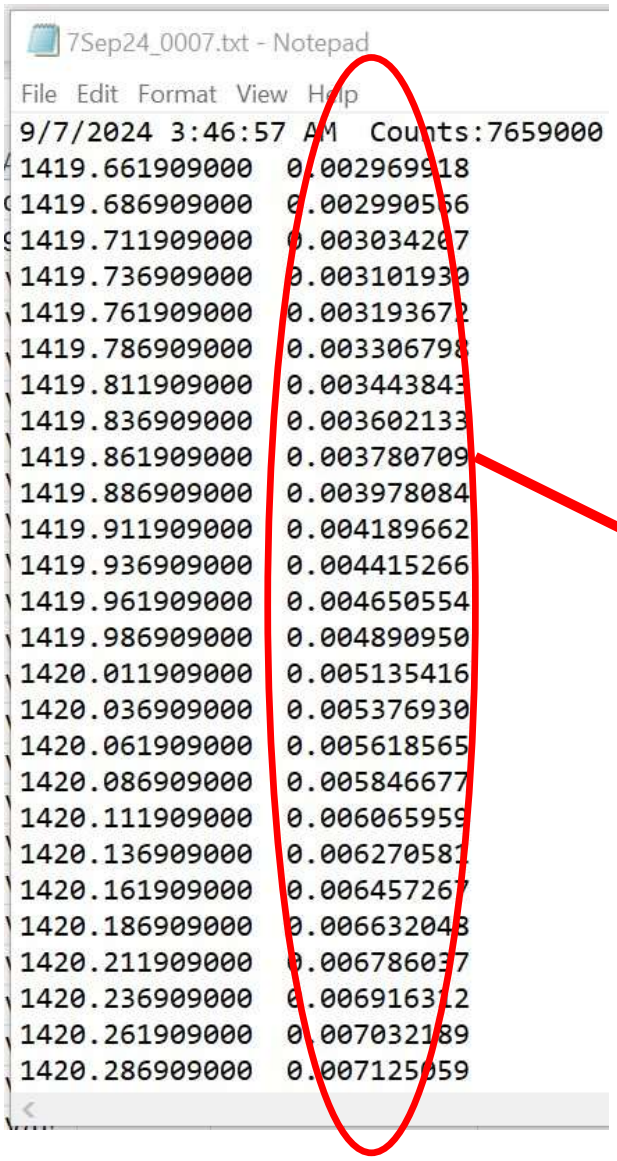
Analyzing Observation Data

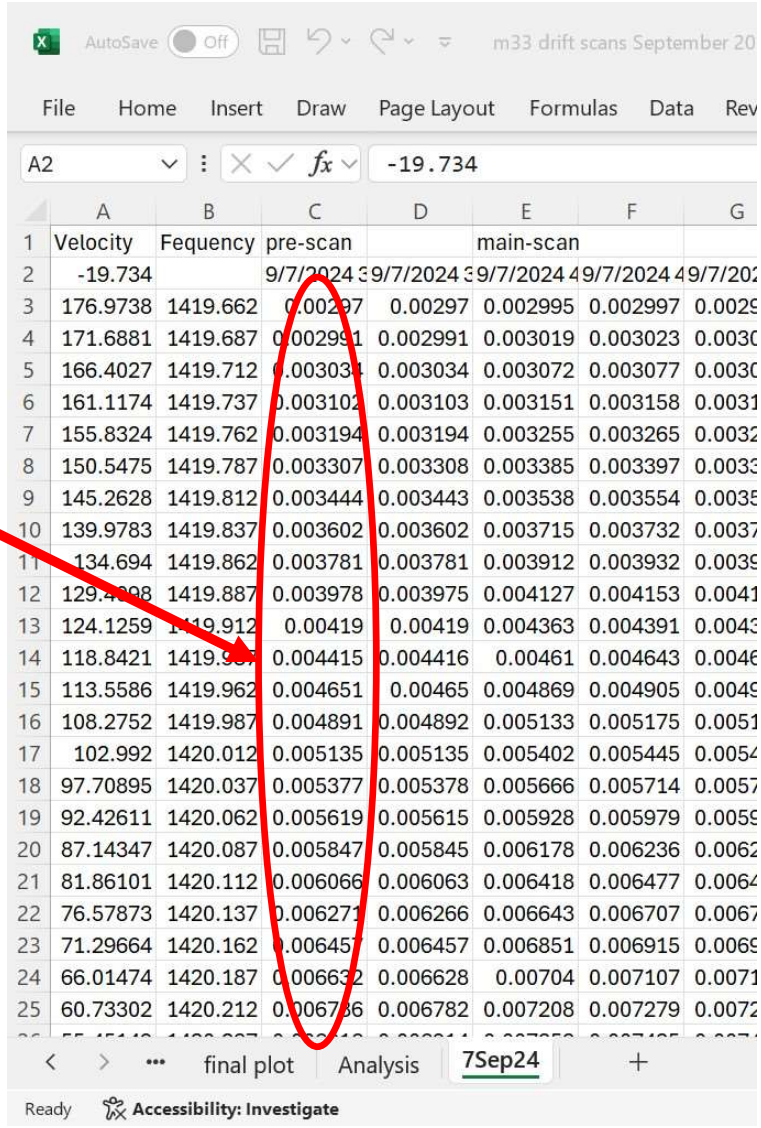
Look at the time stamps on your data files and record which ones correspond to the pre main and post transit times in your plan.



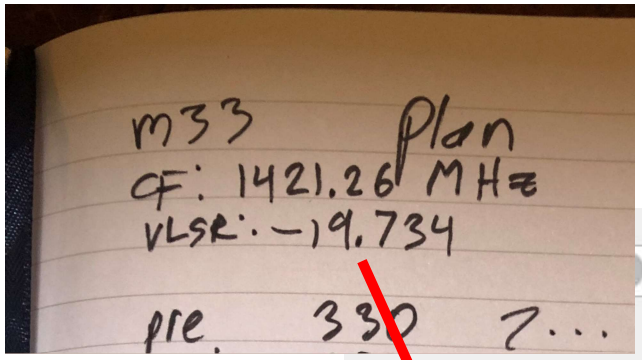


Open a copy of my data analysis spreadsheet and paste the data from these files into the appropriate columns in a new copy of the “Raw Data” sheet and rename the tab to the observation date.





Update the VLSR correction value in cell “A2” to whatever is listed in your plan.



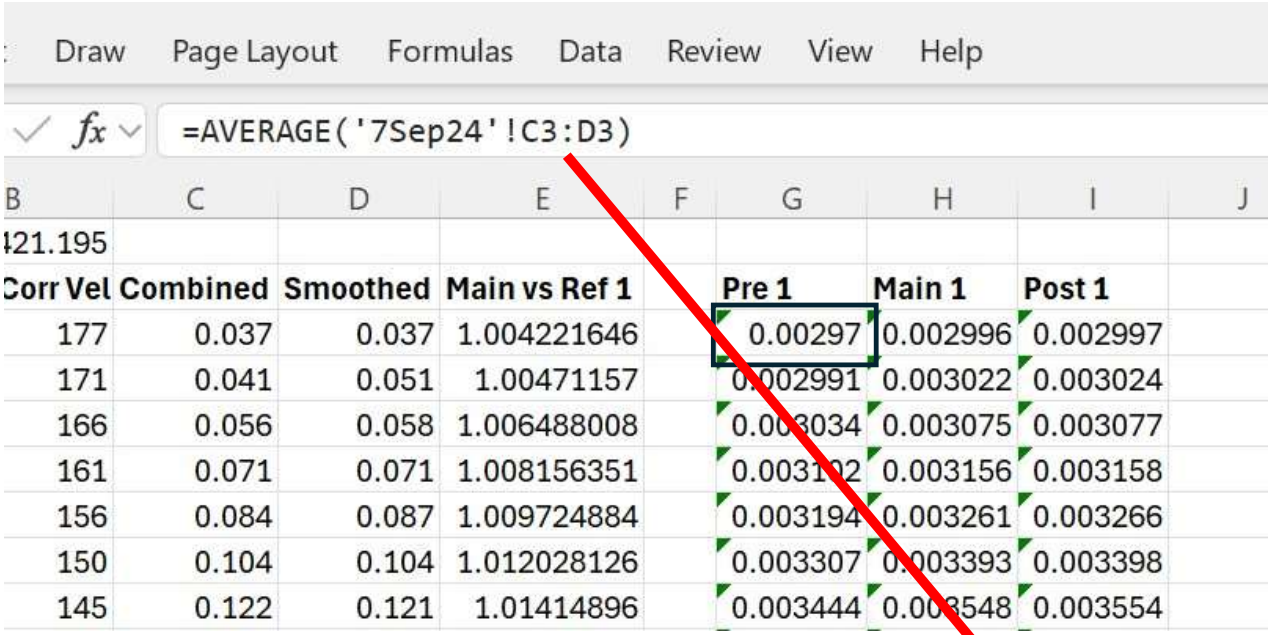
m33 drift scans

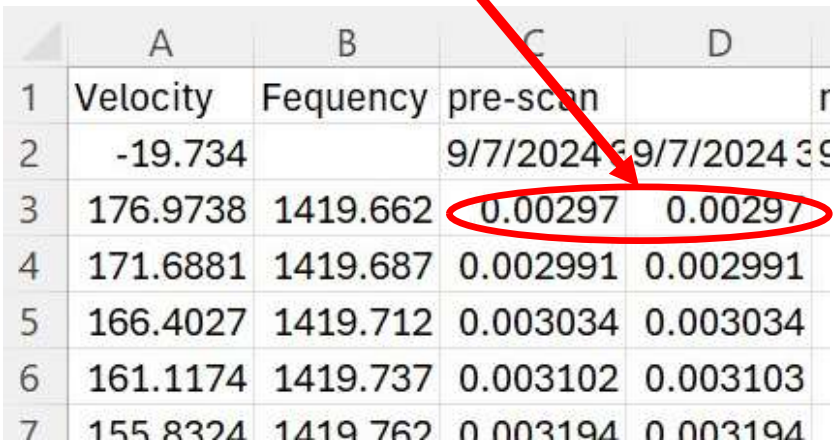
File Home Insert Draw Page Layout Formulas

A2 -19.734

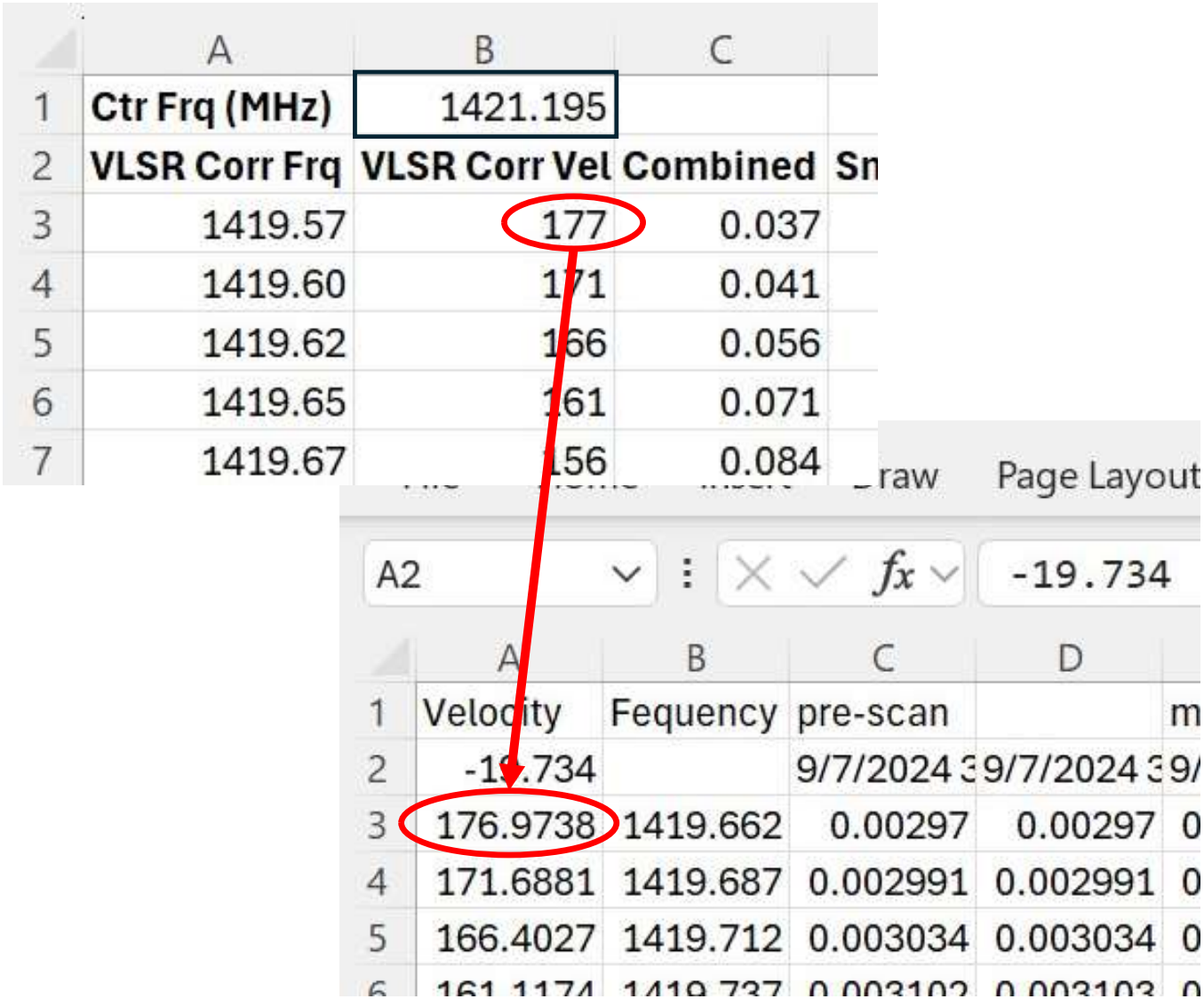
	A	B	C	D	E	
1	Velocity	Fequency	pre-scan		main-scan	
2	-19.734		9/7/2024 3	9/7/2024 3	9/7/2024 4	9/7/
3	176.9738	1419.662	0.00297	0.00297	0.002995	0.0
4	171.6881	1419.687	0.002991	0.002991	0.003019	0.0
5	166.4027	1419.712	0.003034	0.003034	0.003072	0.0
6	161.1174	1419.737	0.003102	0.003103	0.003151	0.0
7	155.8324	1419.762	0.003194	0.003194	0.003255	0.0
8	150.5475	1419.787	0.003307	0.003308	0.003385	0.0
9	145.2628	1419.812	0.003444	0.003443	0.003538	0.0
10	139.9783	1419.837	0.003602	0.003602	0.003715	0.0
11	134.694	1419.862	0.003781	0.003781	0.003912	0.0

Edit the “Pre”, “Main”, and “Post” cells for each category on the “Analysis” sheet to select the correct columns of data from the “Raw Data” Sheet.





If necessary, edit the Center Frequency in cell “B1” until the Velocities in column “B” closely match column “A” on the “Raw Data” sheet.



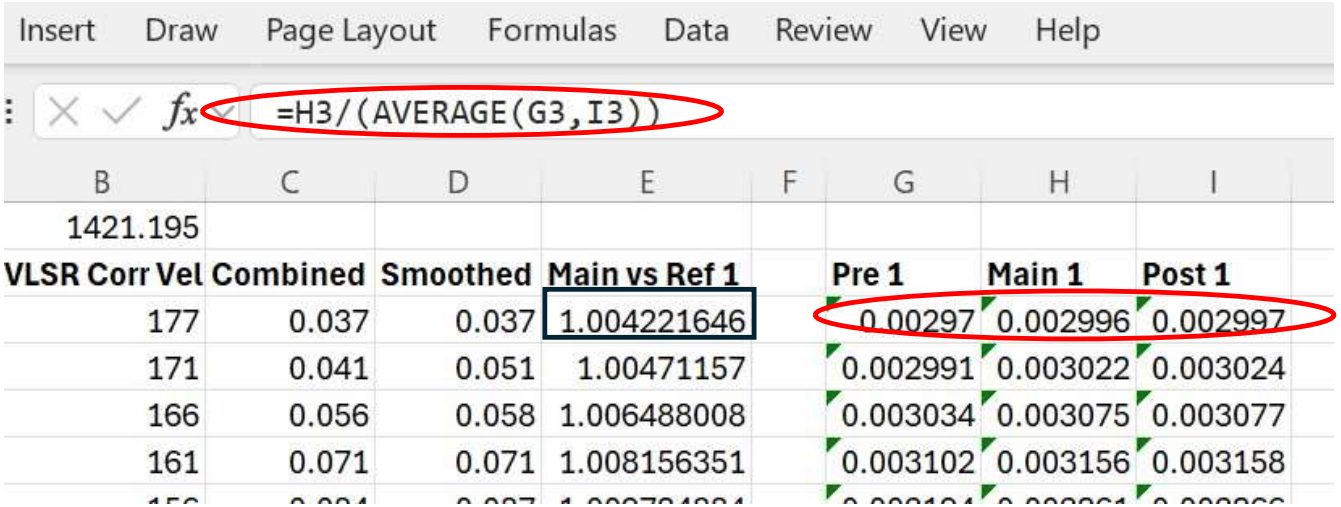
	A	B	C
1	**Ctr Frq (MHz)**	1421.195	
2	**VLSR Corr Frq**	**VLSR Corr Vel**	**Combined**
3	1419.57	177	0.037
4	1419.60	171	0.041
5	1419.62	166	0.056
6	1419.65	161	0.071
7	1419.67	156	0.084

raw Page Layout

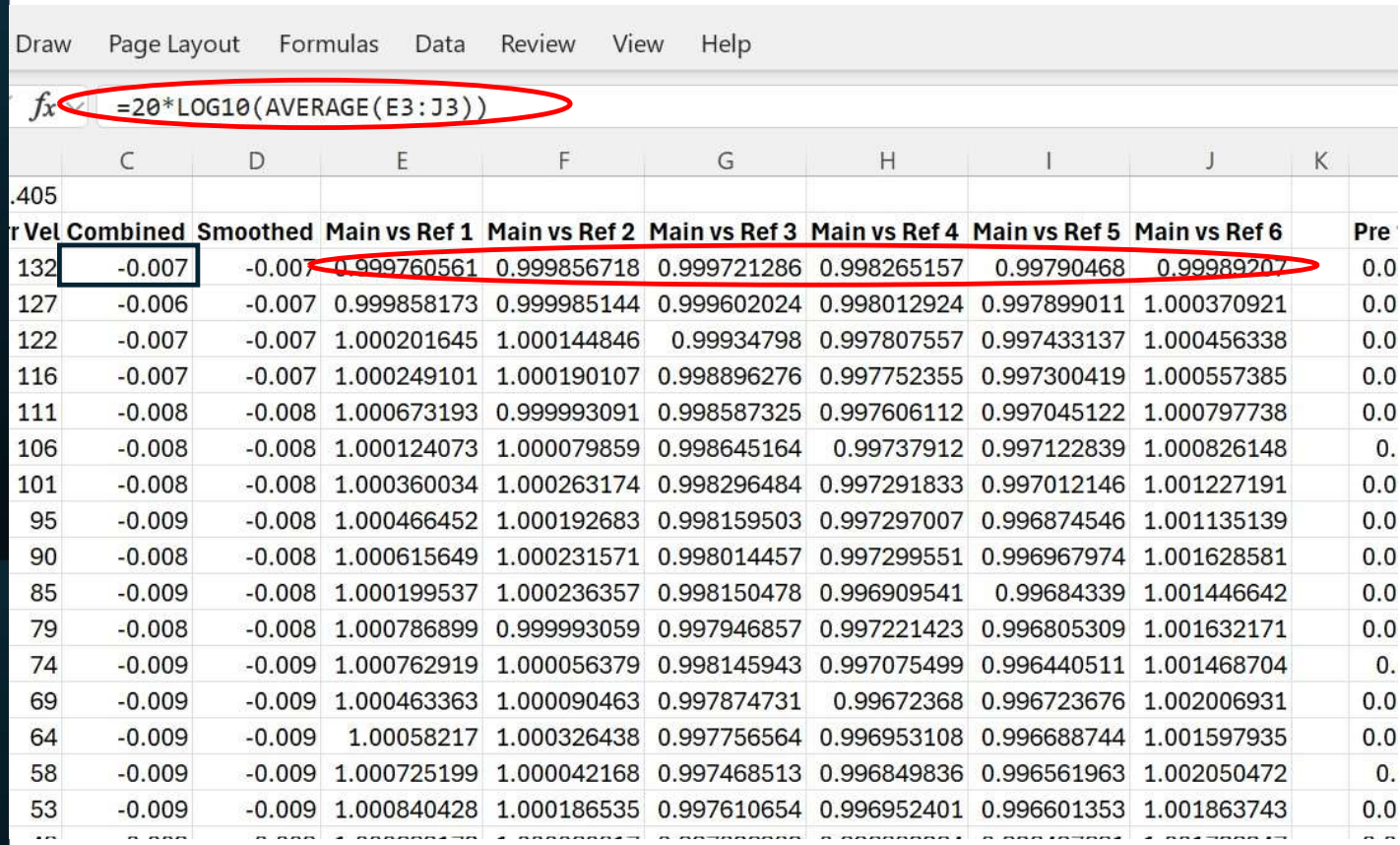
A2 -19.734

	A	B	C	D	
1	Velocity	Fequency	pre-scan		m
2	-19.734		9/7/2024 3	9/7/2024 3	9/
3	176.9738	1419.662	0.00297	0.00297	0
4	171.6881	1419.687	0.002991	0.002991	0
5	166.4027	1419.712	0.003034	0.003034	0
6	161.1174	1419.737	0.003102	0.003103	0

Edit the formula in the “Main vs Ref” column to point to the appropriate “Pre”, “Main”, and “Post” cells.



Edit the “Combined” cells to average all “Main vs Ref” Columns.
This column also converts the raw amplitude ratios to dB using 20 Log.



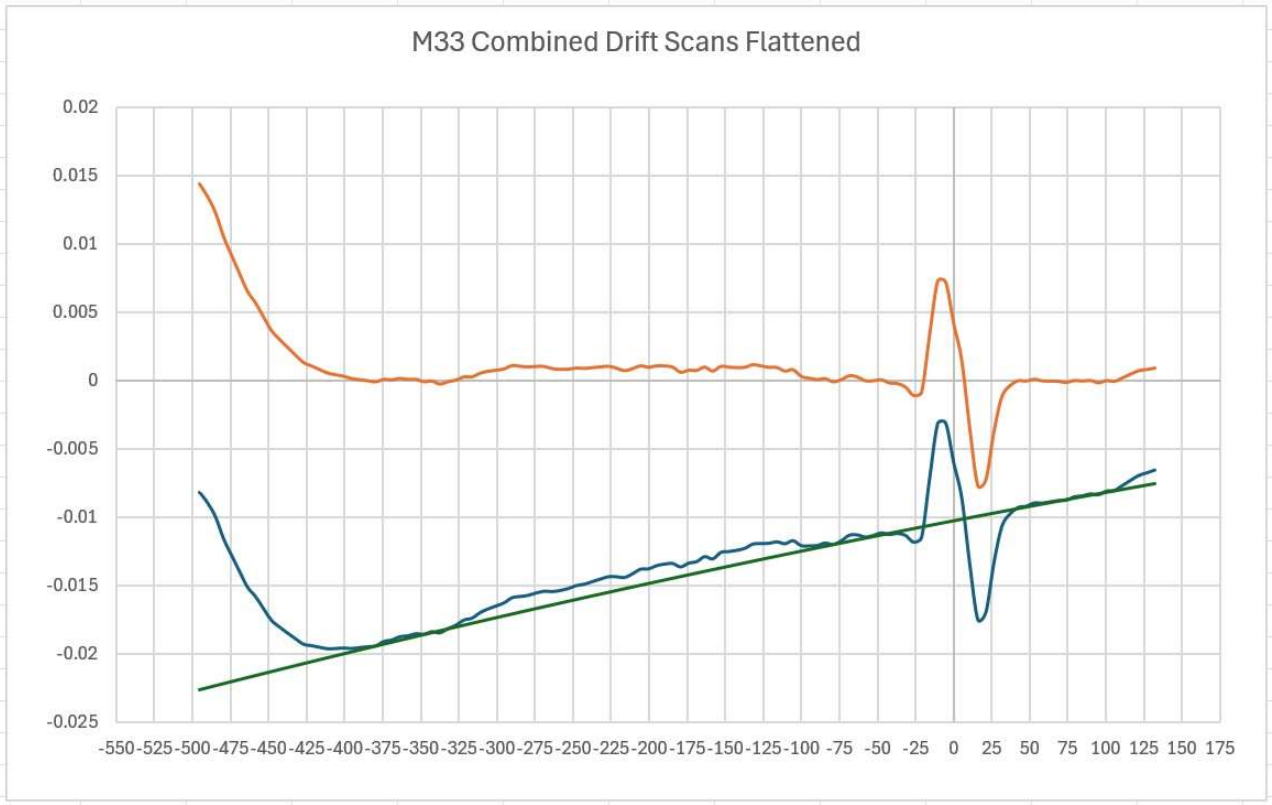
Draw Page Layout Formulas Data Review View Help

fx =20*LOG10(AVERAGE(E3:J3))

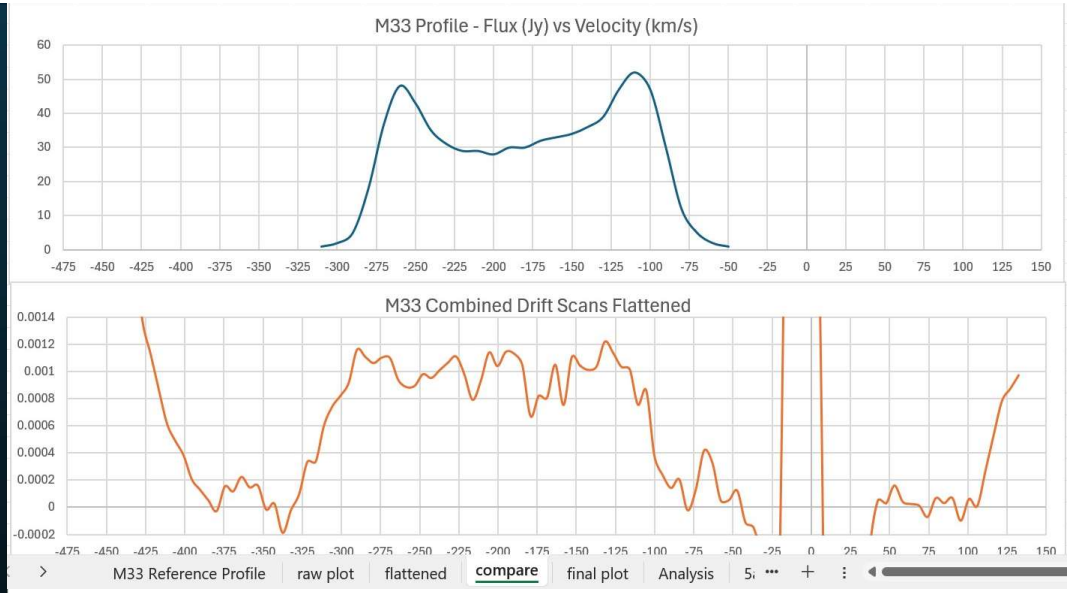
	C	D	E	F	G	H	I	J	K
.405									
r Vel	Combined	Smoothed	Main vs Ref 1	Main vs Ref 2	Main vs Ref 3	Main vs Ref 4	Main vs Ref 5	Main vs Ref 6	Pre
132	-0.007	-0.007	0.999760561	0.999856718	0.999721286	0.998265157	0.99790468	0.99989207	0.0
127	-0.006	-0.007	0.999858173	0.999985144	0.999602024	0.998012924	0.997899011	1.000370921	0.0
122	-0.007	-0.007	1.000201645	1.000144846	0.99934798	0.997807557	0.997433137	1.000456338	0.0
116	-0.007	-0.007	1.000249101	1.000190107	0.998896276	0.997752355	0.997300419	1.000557385	0.0
111	-0.008	-0.008	1.000673193	0.999993091	0.998587325	0.997606112	0.997045122	1.000797738	0.0
106	-0.008	-0.008	1.000124073	1.000079859	0.998645164	0.99737912	0.997122839	1.000826148	0.
101	-0.008	-0.008	1.000360034	1.000263174	0.998296484	0.997291833	0.997012146	1.001227191	0.0
95	-0.009	-0.008	1.000466452	1.000192683	0.998159503	0.997297007	0.996874546	1.001135139	0.0
90	-0.008	-0.008	1.000615649	1.000231571	0.998014457	0.997299551	0.996967974	1.001628581	0.0
85	-0.009	-0.008	1.000199537	1.000236357	0.998150478	0.996909541	0.99684339	1.001446642	0.0
79	-0.008	-0.008	1.000786899	0.999993059	0.997946857	0.997221423	0.996805309	1.001632171	0.0
74	-0.009	-0.009	1.000762919	1.000056379	0.998145943	0.997075499	0.996440511	1.001468704	0.
69	-0.009	-0.009	1.000463363	1.000090463	0.997874731	0.99672368	0.996723676	1.002006931	0.0
64	-0.009	-0.009	1.00058217	1.000326438	0.997756564	0.996953108	0.996688744	1.001597935	0.0
58	-0.009	-0.009	1.000725199	1.000042168	0.997468513	0.996849836	0.996561963	1.002050472	0.
53	-0.009	-0.009	1.000840428	1.000186535	0.997610654	0.996952401	0.996601353	1.001863743	0.0

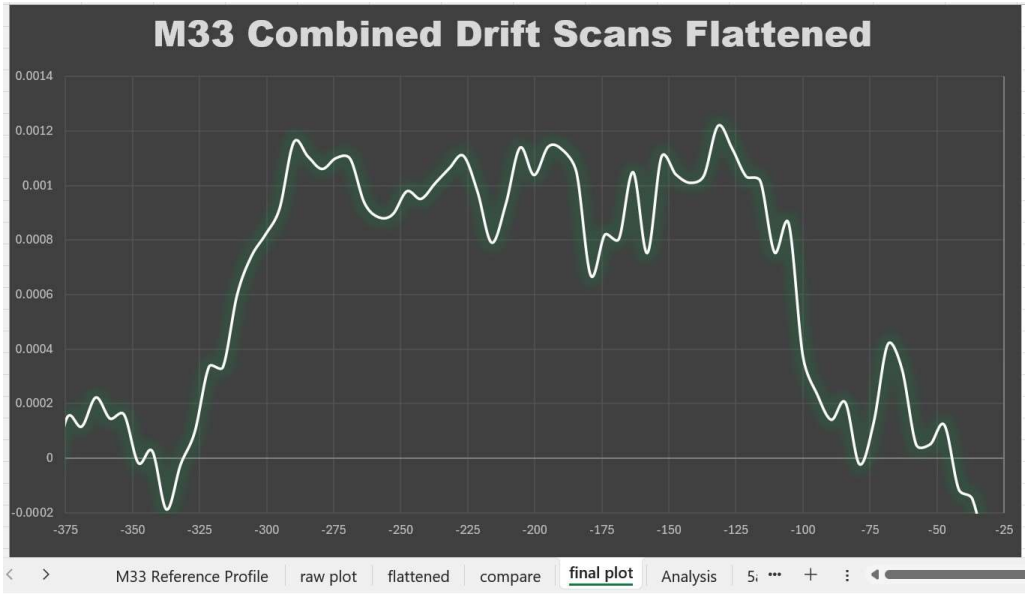
Edit the flattening polynomial coefficients on the “Flattened” sheet until the background on either side of the expected profile region in the orange plot is reasonably flat and at zero.

5th
0
4th
0
3rd
0
2nd
-7.00E-09
1st
2.15E-05
0th
-0.0102



Adjust the horizontal and vertical scales on the “Compare” and “Final” Plots as desired to display the spectral profile as nicely as possible.





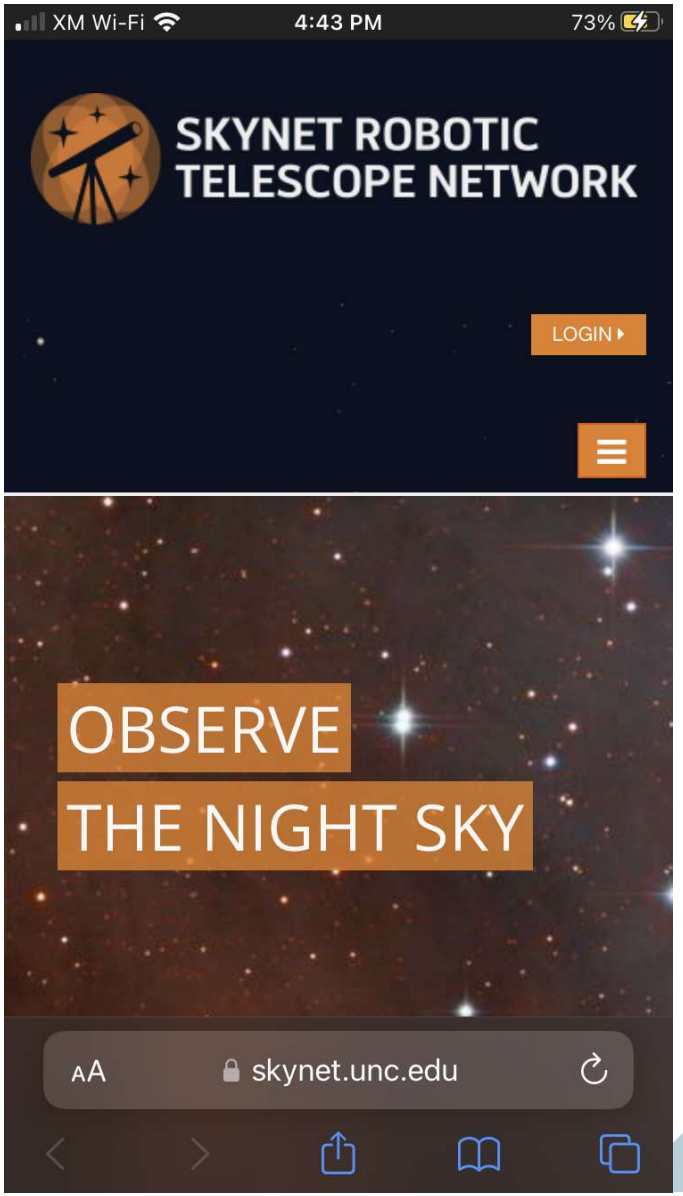
Observing with the Green Bank 20 Meter Dish

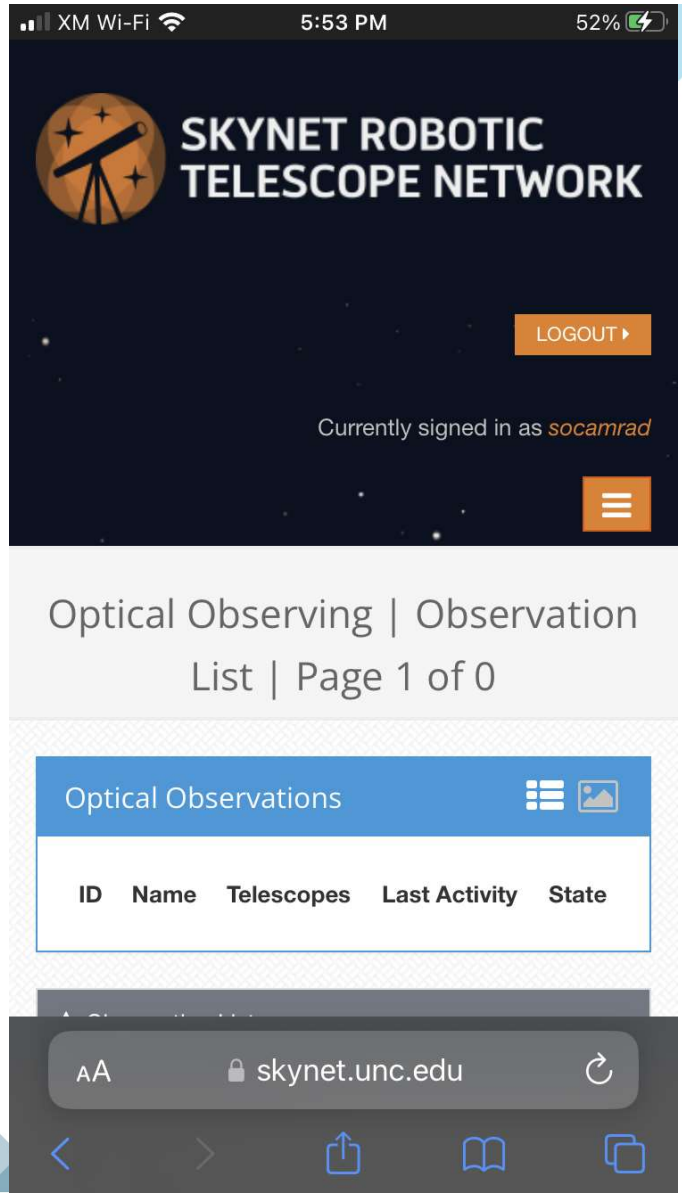
Observation Settings

- L-Band
- High Resolution
- Center Frequency set to 1420.4 MHz
- 1 second “ON”
- 1 second “OFF”
- 10 repetitions for a total of 10 seconds for each
- 1.5 degrees Az and El offset for “OFF”

Open your browser and go to https://www.skynet.unc.edu.

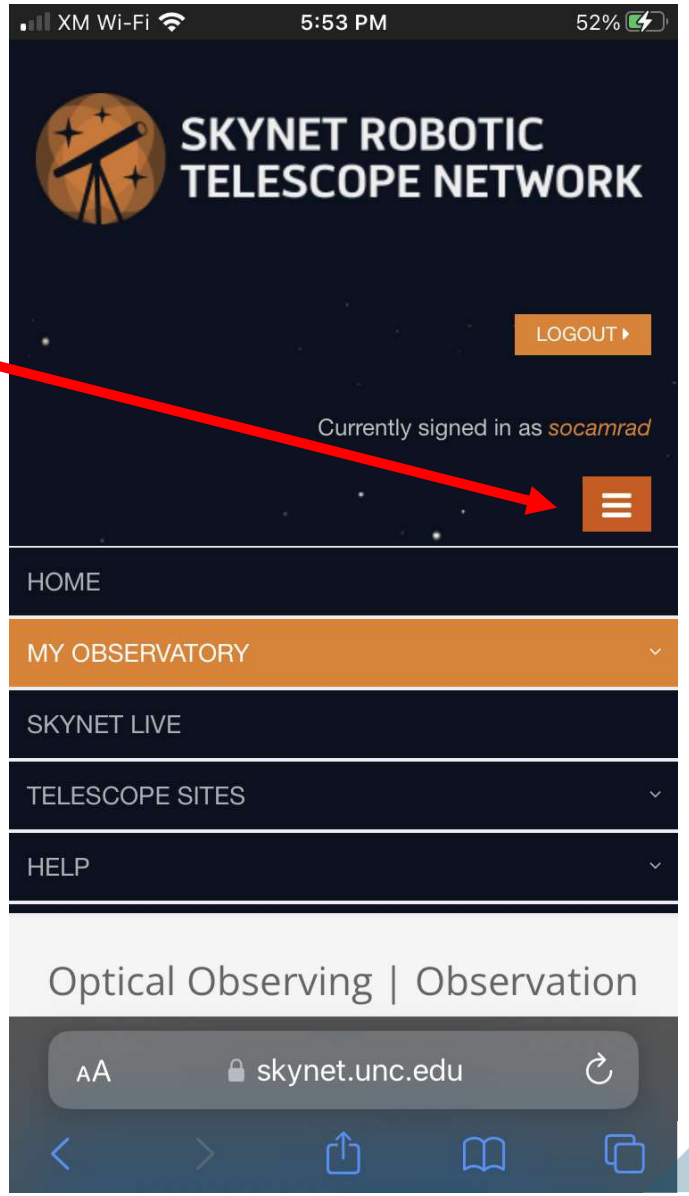
Log-in using the SARA username and password which you can get by emailing Stephen Tzikas at: Tzikas@alum.rpi.edu.

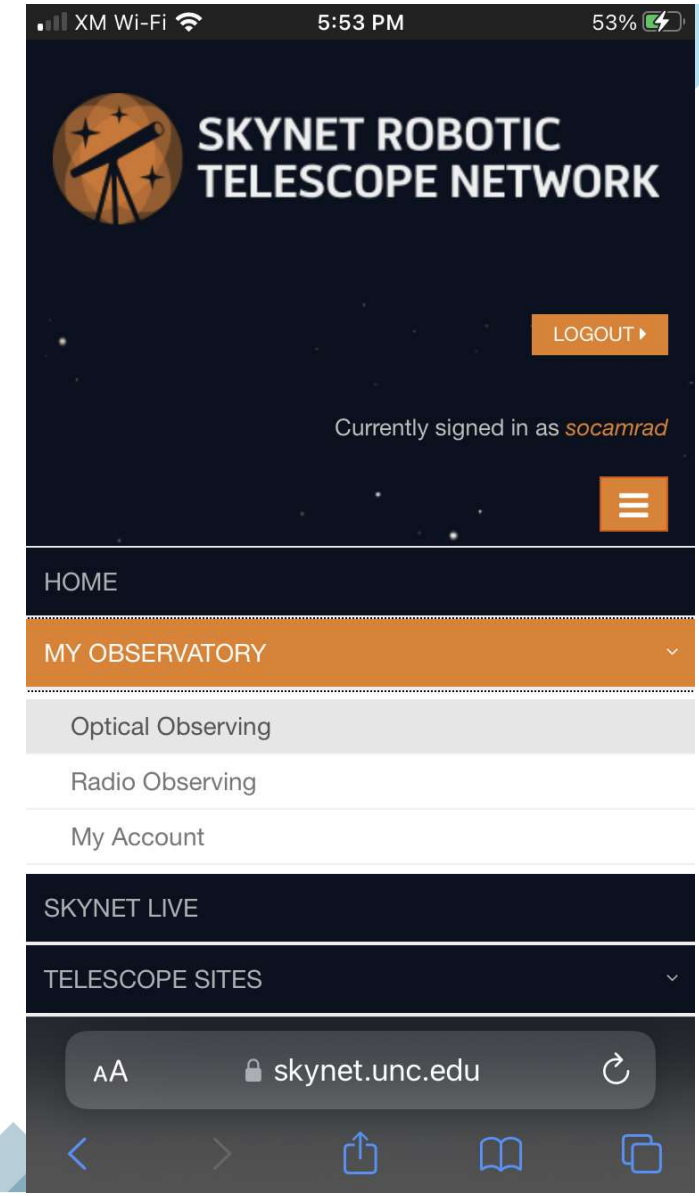




Click on the menu icon in the top left.

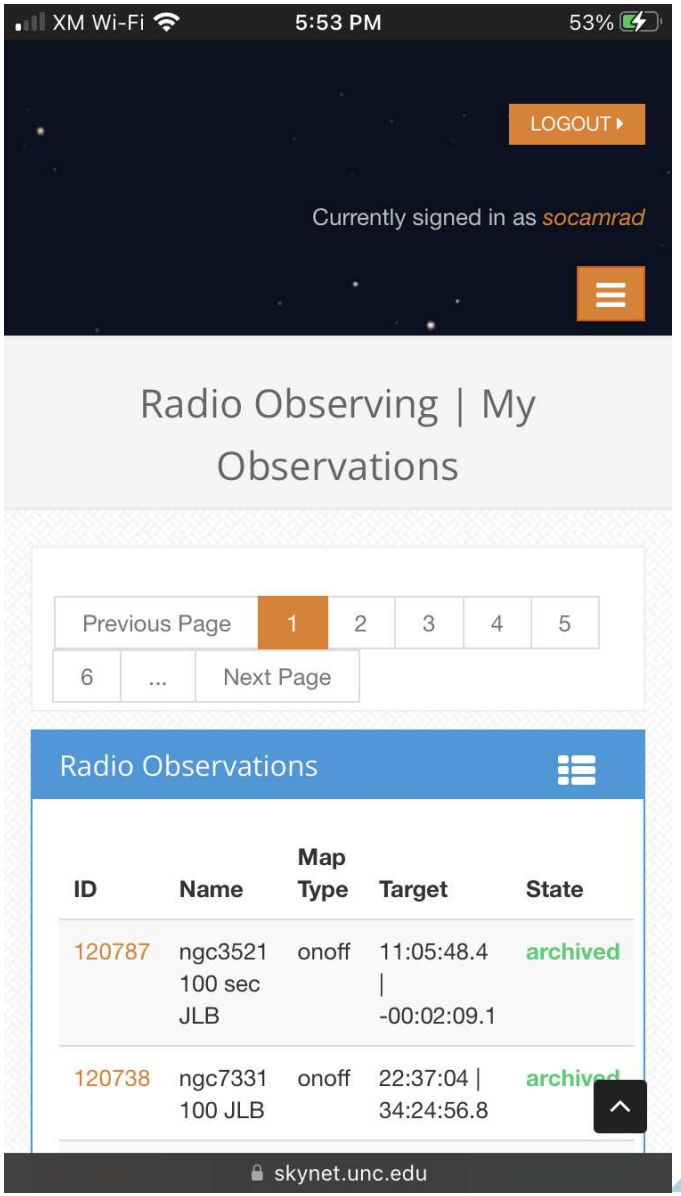
Select the “My Observatory” tab and select the “Radio Observing” option.

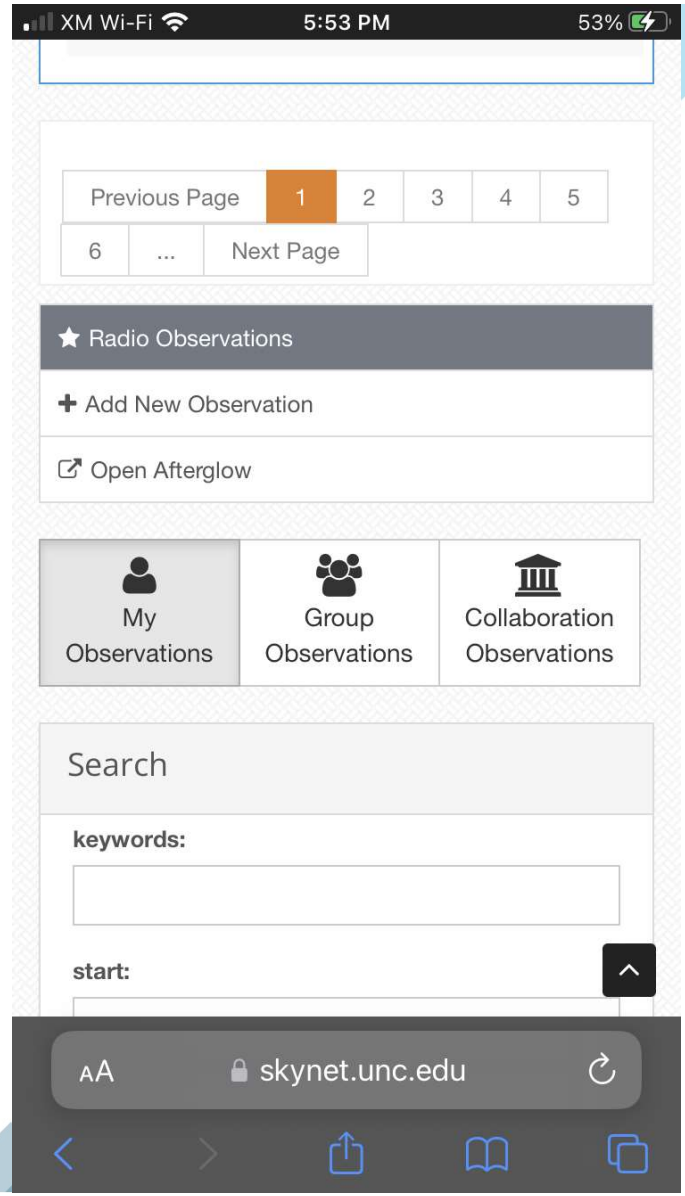




You will see a list of observations that are pending or recently completed.

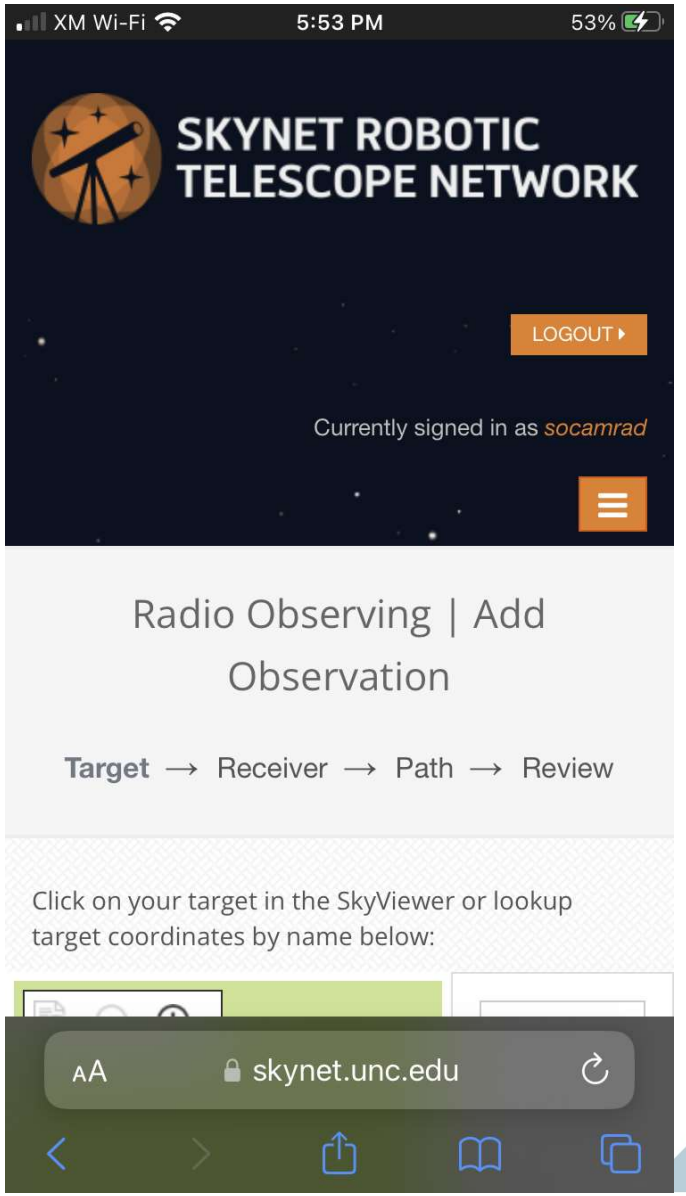
Scroll down to the bottom of the page and select “+ Add New Observation”.

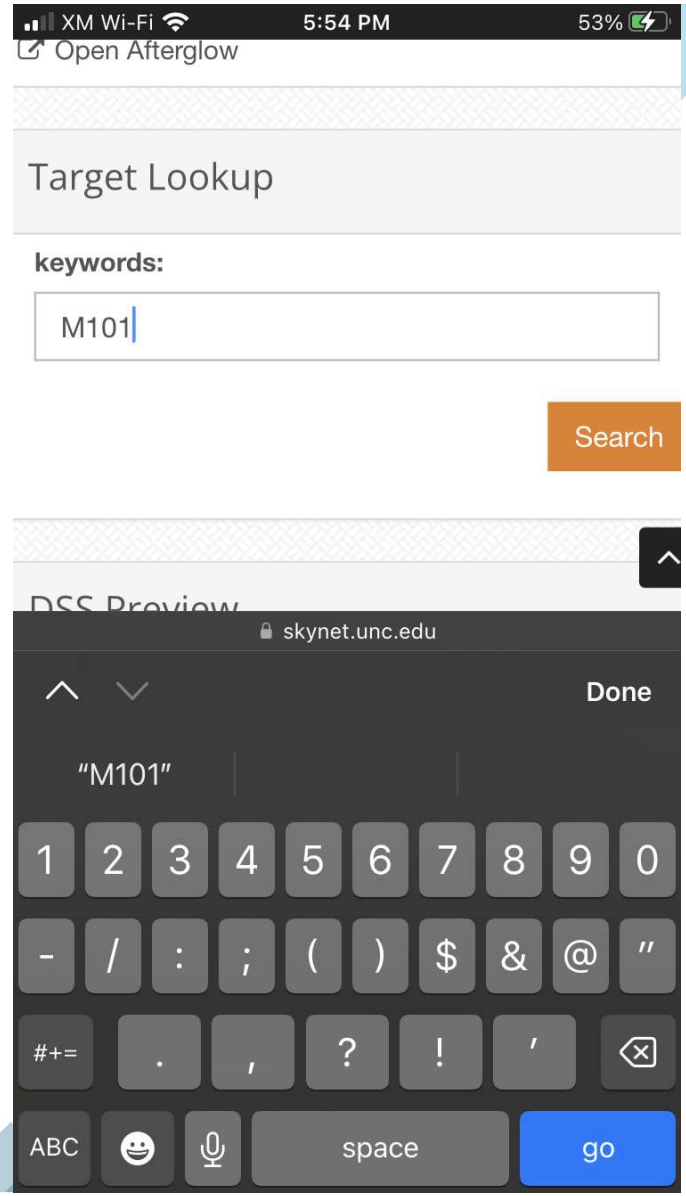




Scroll down the page until you see the “keywords:” box and type in the designation or name of the galaxy you want to observe.

You can also enter coordinates exactly instead of using the keyword search.





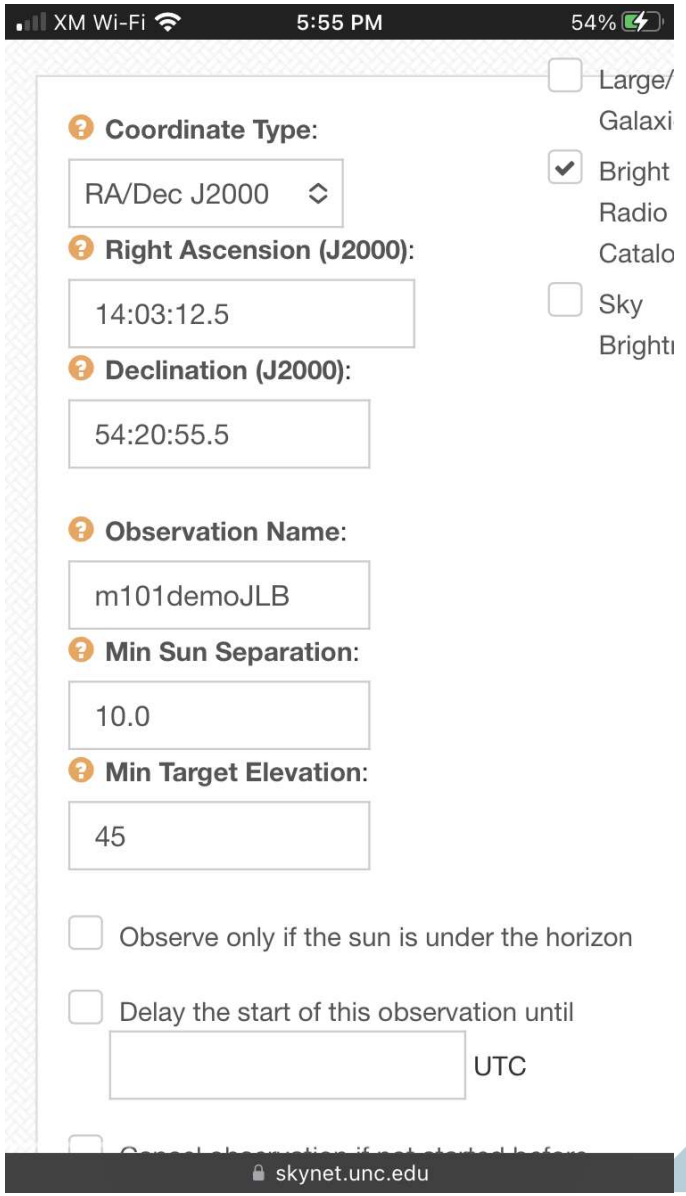
Scroll up to the top and you should see the coordinates already populated for the object you entered.

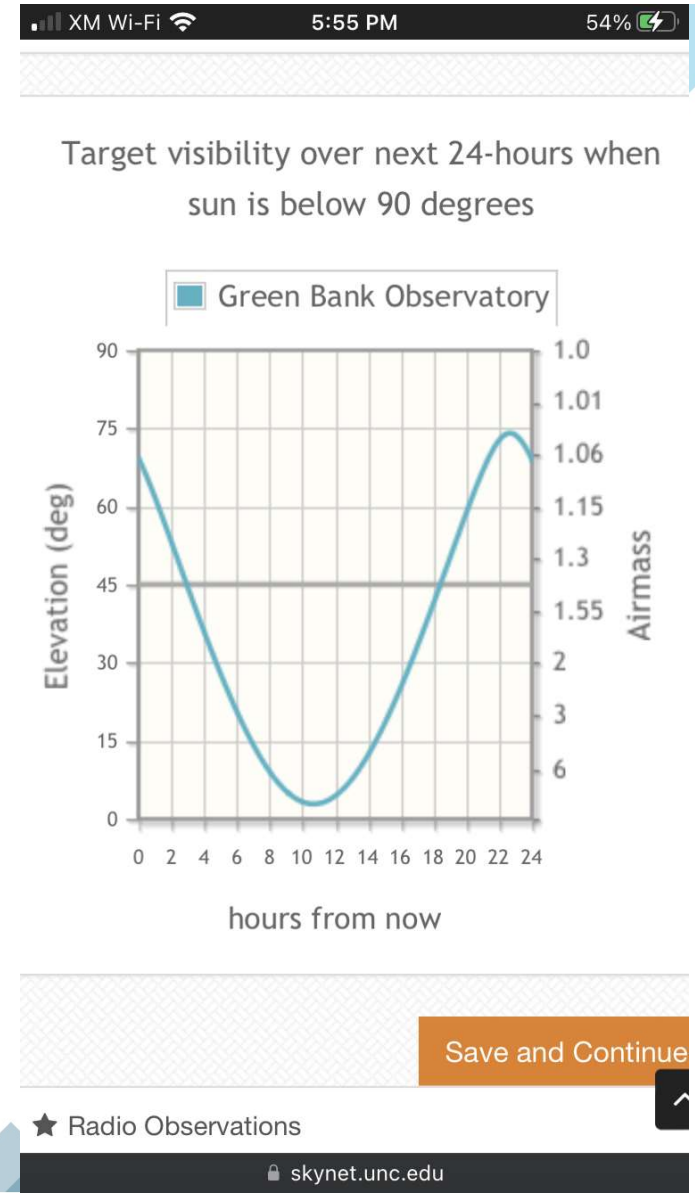
Edit the Observation Name to add your initials.

You can change the Min Sun Separation and Min Target Elevation as desired.

A chart will show when the object will be in range of the observation settings you selected.

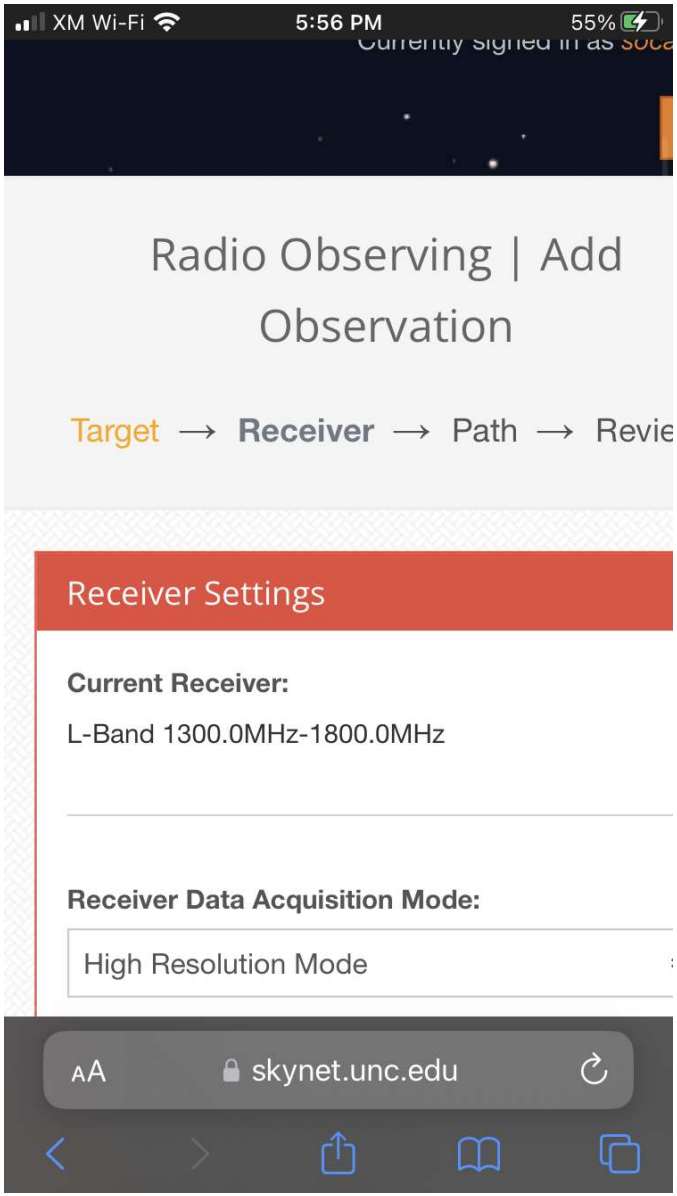
Hit “Save and Continue” to go to the next screen.

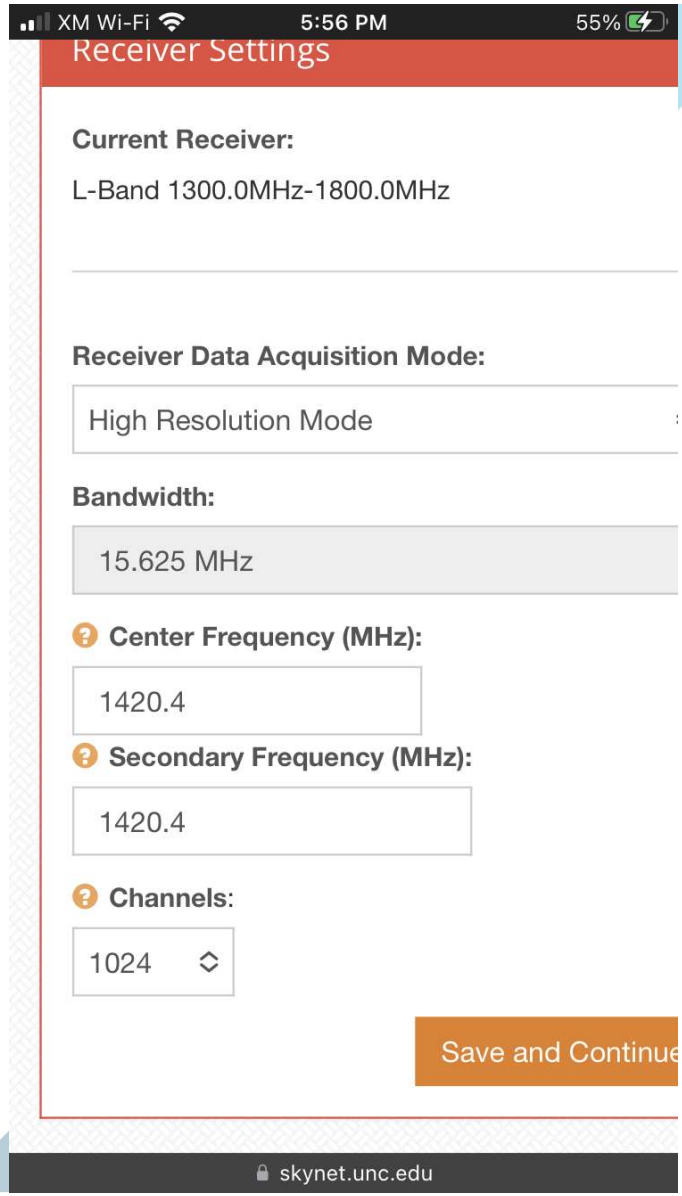




Select “High Resolution Mode”.

Set both the center frequency and secondary frequency to 1420.4 MHz.





Make the following selections:

Path Type “On/Off”

Duration “1”

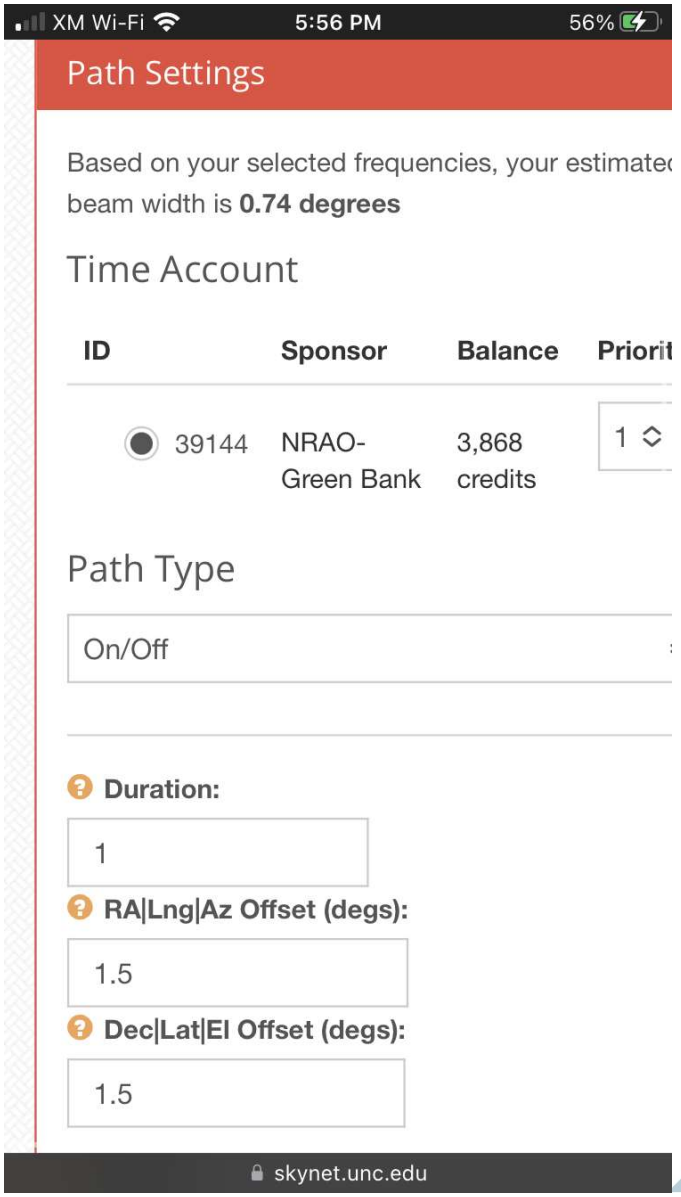
RA[Lng]Az Offset “1.5”

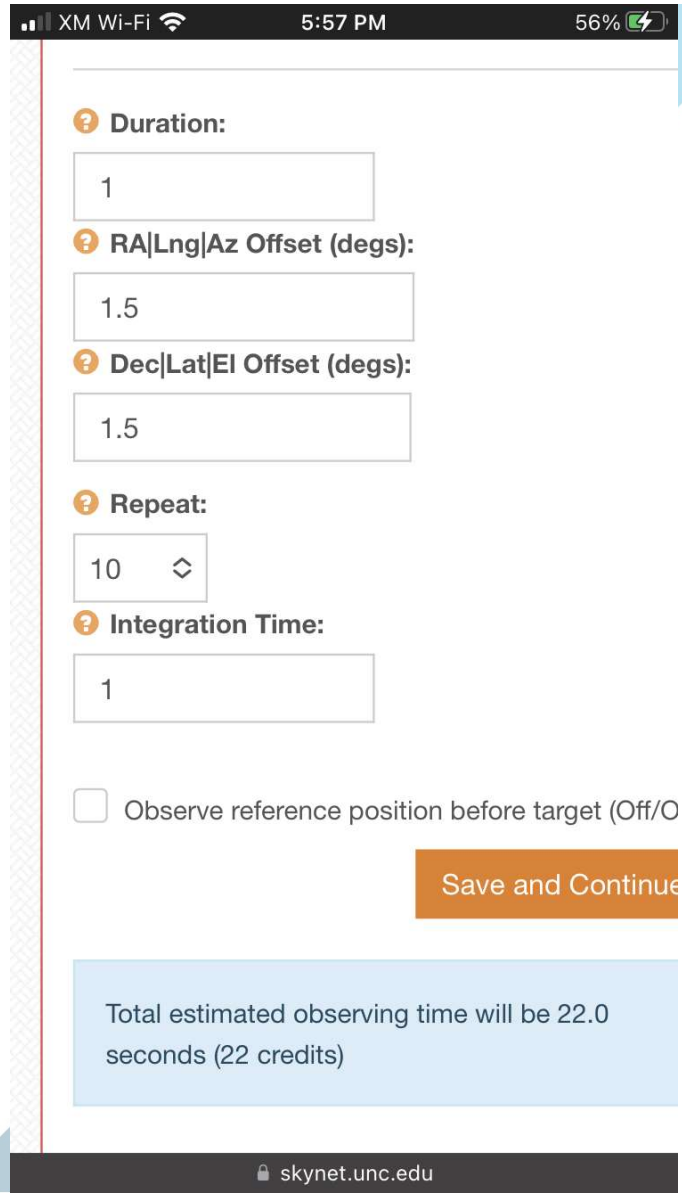
Dec[Lat]El Offset “1.5”

Repeat “10”

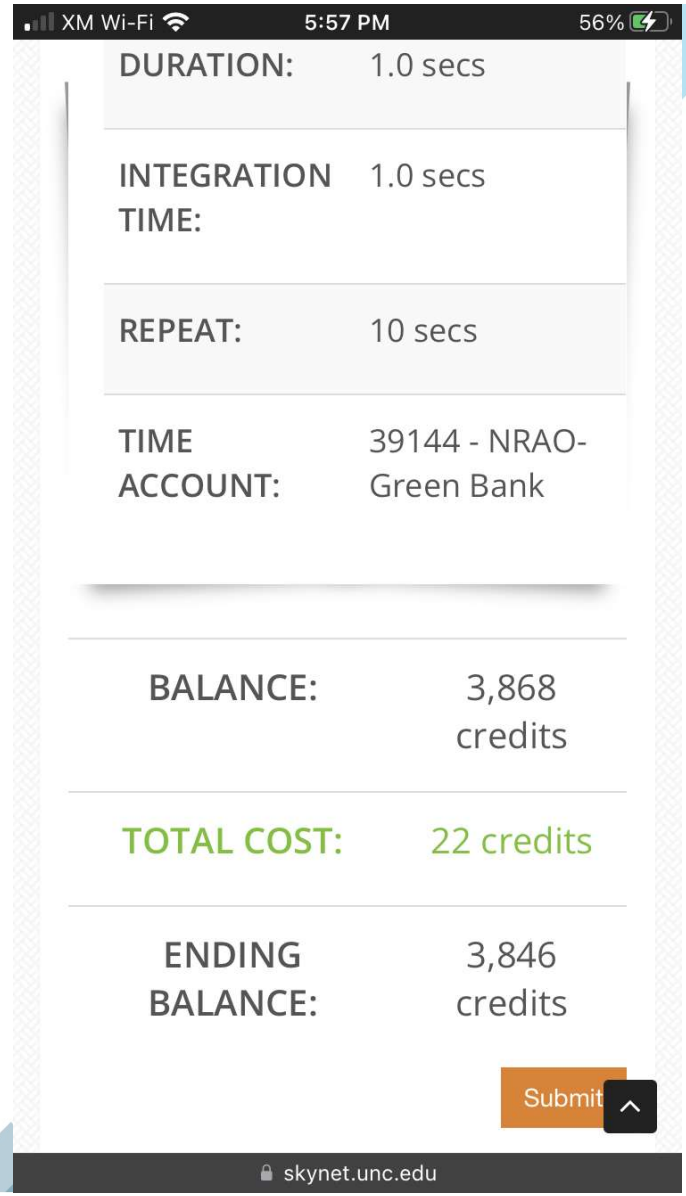
Integration time “1”

Hit “Save and Continue”.

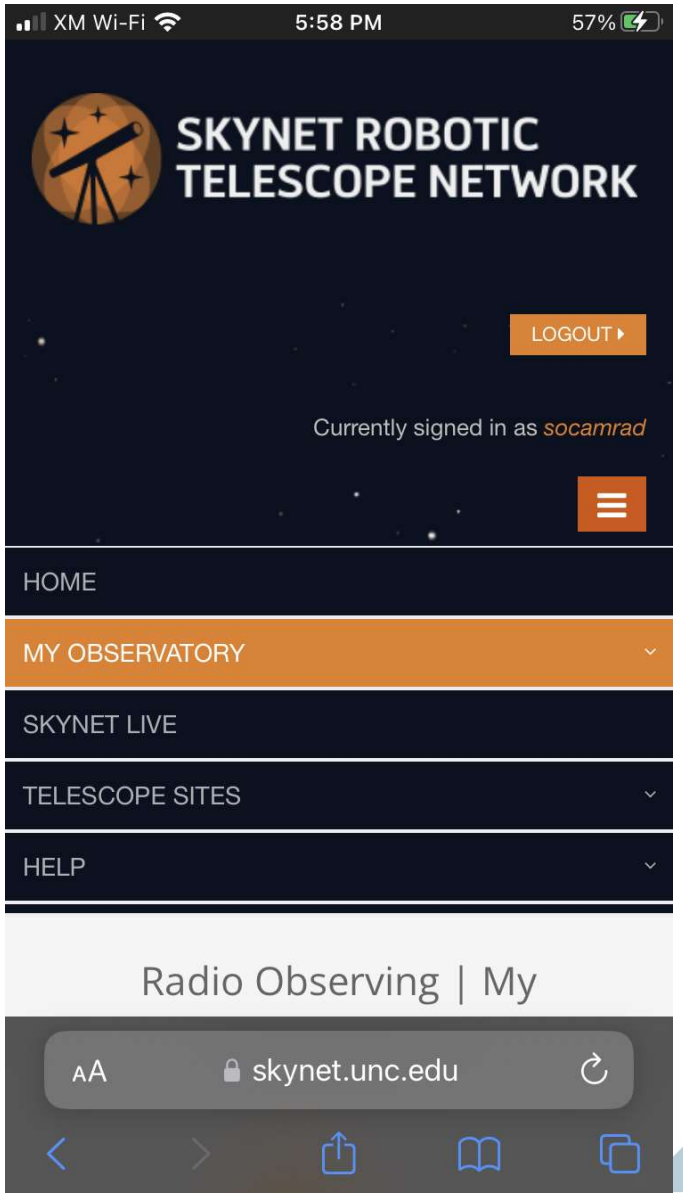


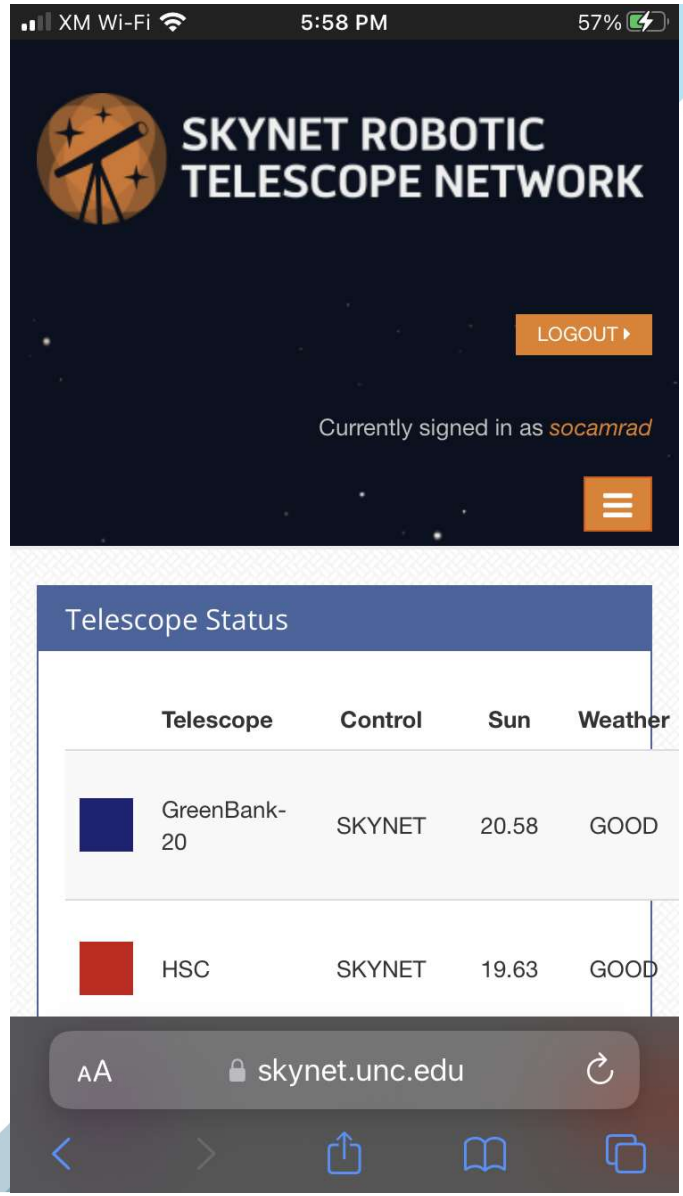


Double-check all of your selections and if they look correct, hit “Submit”.

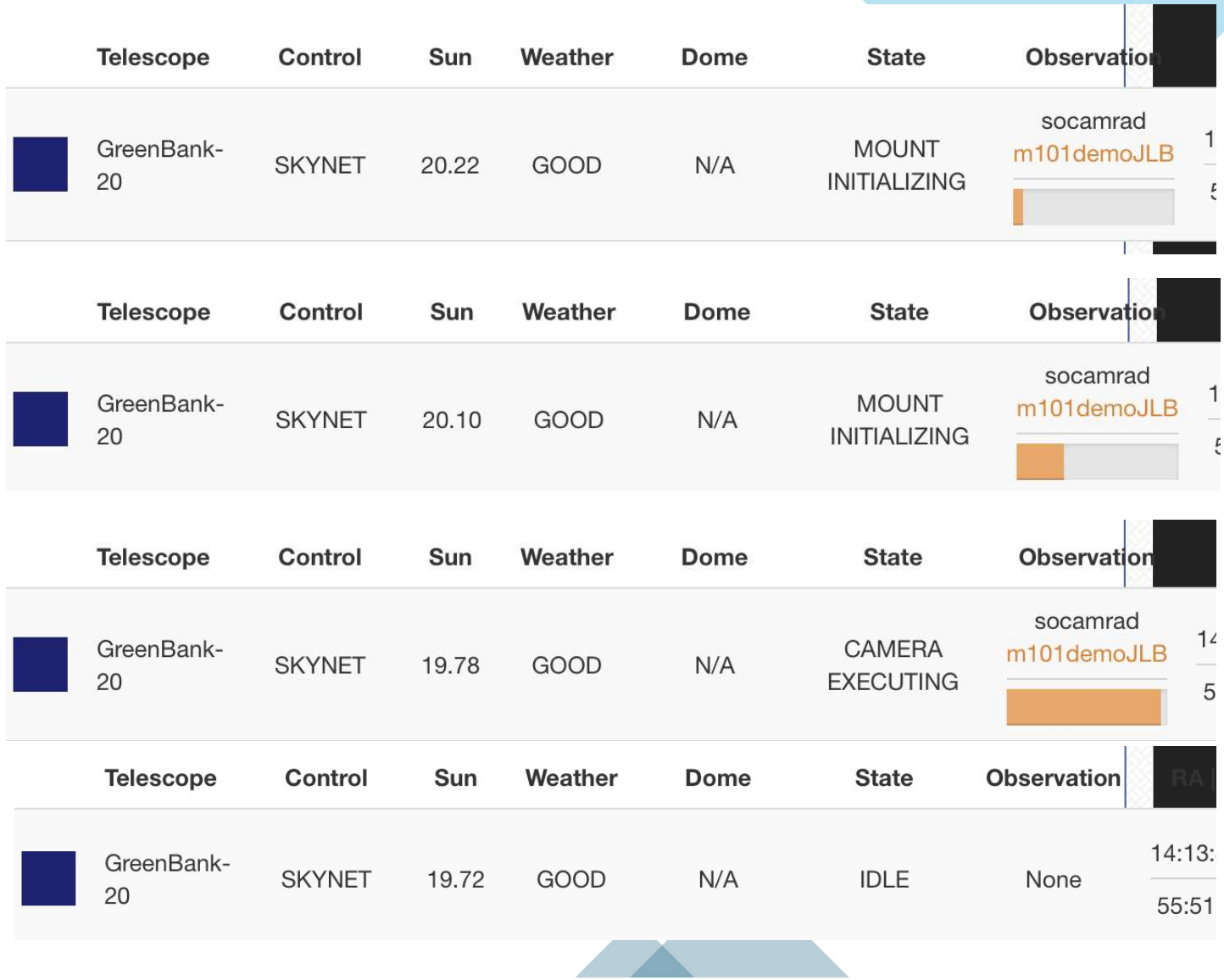


Select “Skynet Live” to see the status of the Green-Bank 20 telescope.





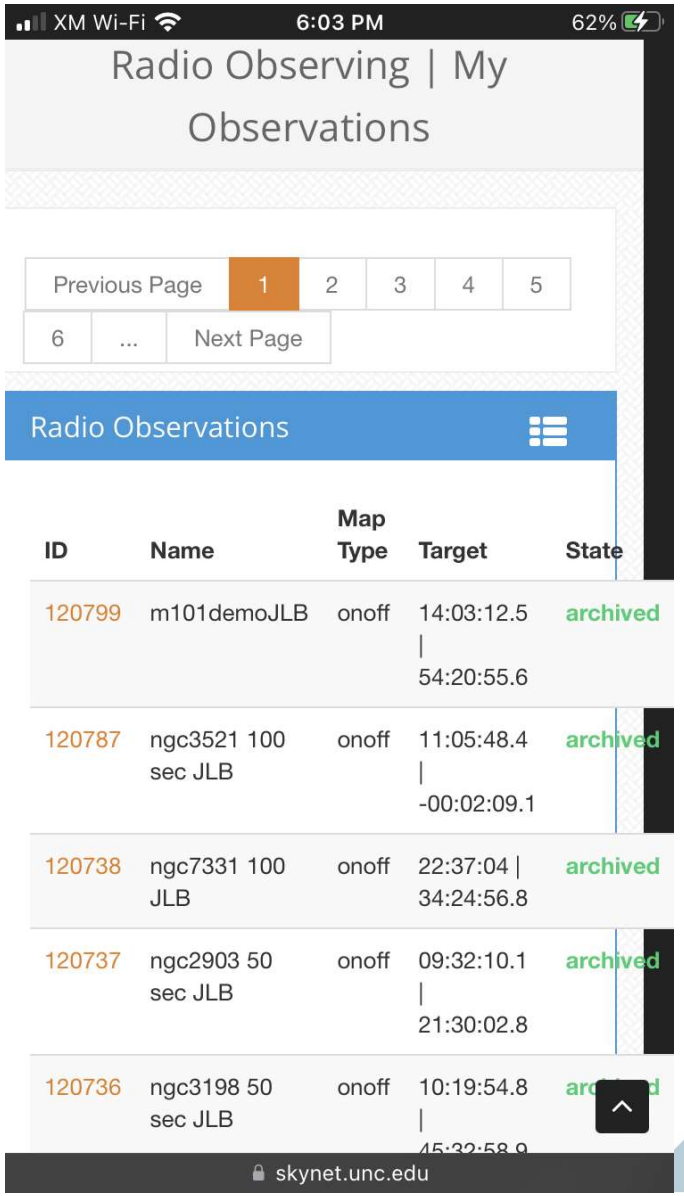
From here, you can watch the observation status in progress.

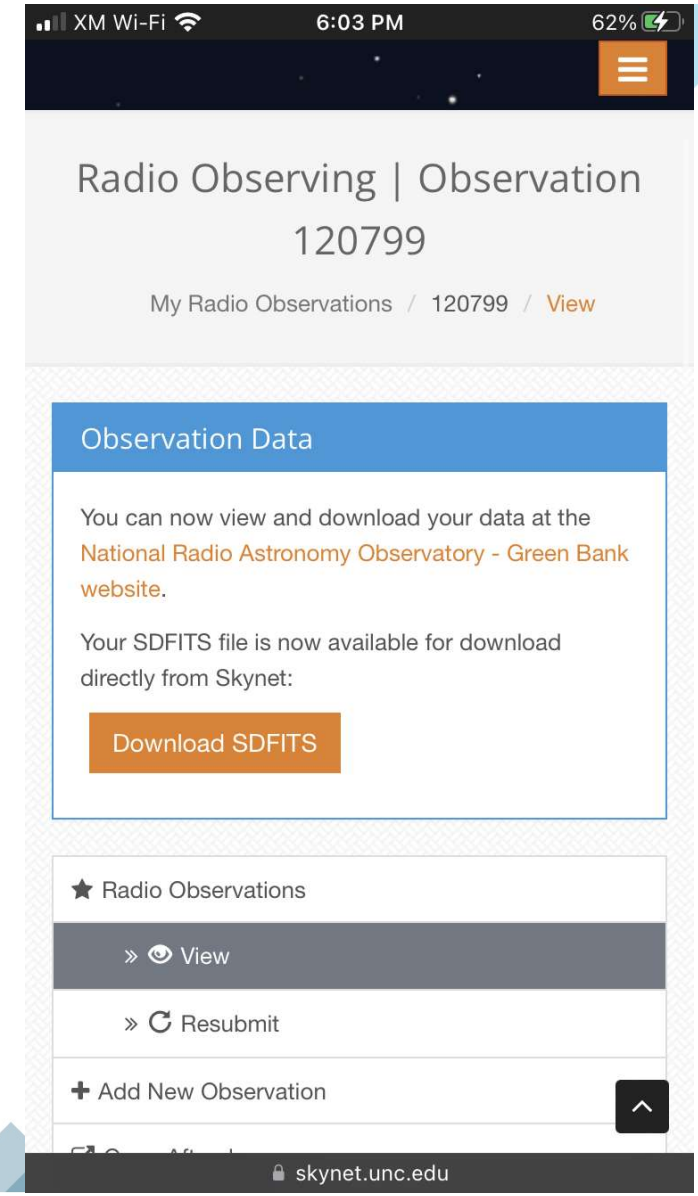


	Telescope	Control	Sun	Weather	Dome	State	Observation
	GreenBank-20	SKYNET	20.22	GOOD	N/A	MOUNT INITIALIZING	socamrad m101demoJLB
	Telescope	Control	Sun	Weather	Dome	State	Observation
	GreenBank-20	SKYNET	20.10	GOOD	N/A	MOUNT INITIALIZING	socamrad m101demoJLB
	Telescope	Control	Sun	Weather	Dome	State	Observation
	GreenBank-20	SKYNET	19.78	GOOD	N/A	CAMERA EXECUTING	socamrad m101demoJLB
	Telescope	Control	Sun	Weather	Dome	State	Observation
	GreenBank-20	SKYNET	19.72	GOOD	N/A	IDLE	None

Select “Radio Observing” again and you will see that the status is “archived” which means your observation results are now ready to view and/or download.

When you click on the ID of the observation you will see a link to view and download your data.

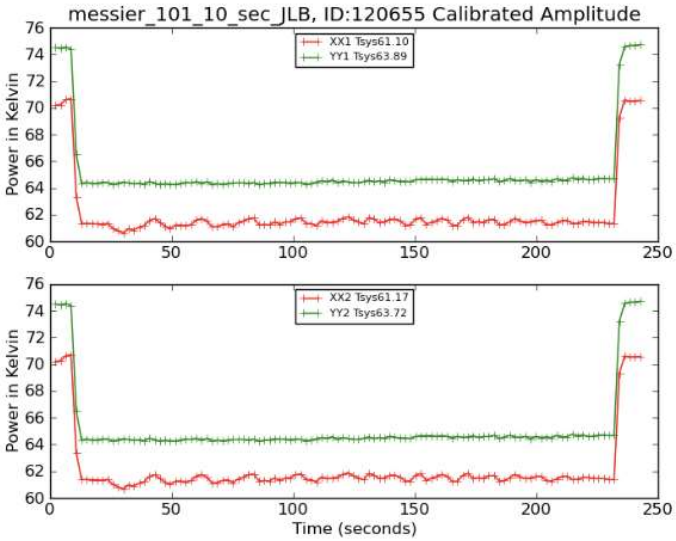




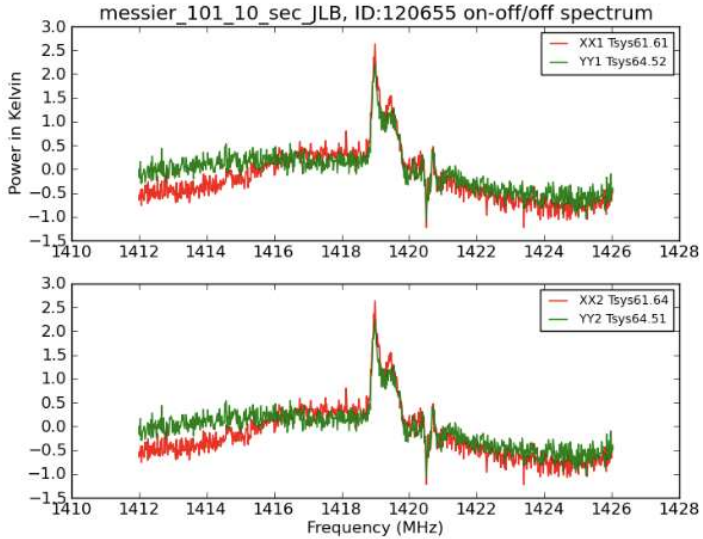
Continuum Raw data Calibrated Calibration Info	**Spectra** Calibrated off-source On/Off Cal	2024-08-23 21:42:32 (UT) Observer: socamrad_21318 HIRES onoff; filter 1355_1435; 243 secs	Latest Log	20m Info 20m Skynet	
Data File Description.			Skynet: my obs		

{Raw data at 20m-data:/raid/scratch/cyborg/SkynetData/Skynet_60545_messier_101_10_sec_JLB_120655/Cyborg }

If you click on that link, you will see power vs time and spectral plots of your observation data.



On-Off/Off spectrum :



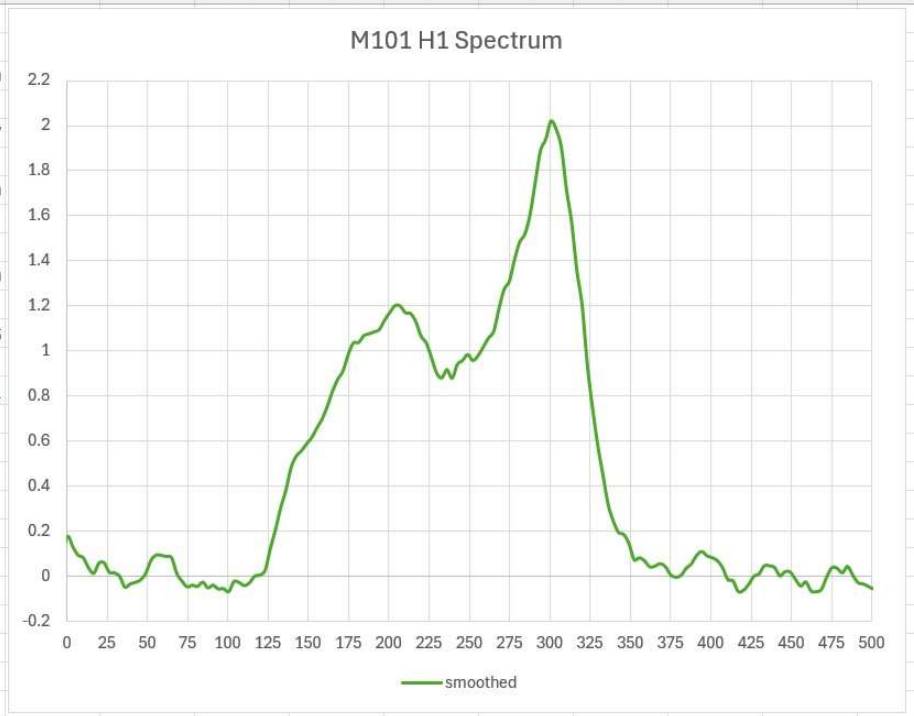
Live Spectrum

If you click on the link in the cell marked “Spectra” it will bring up a text file with the data which you can download.

```
#     FILENAME=Skynet_60545_messier_101_10_sec_JLB_12065
#     BASENAME=Skynet_60545_messier_101_10_sec_JLB_12065
#      CONTROL=SKYNET
#     PROJCODE=Skynet_60545_messier_101_10_sec_JLB_12065
#     DATAROOT=/raid/scratch/cyborg/SkynetData
#      DATADIR=/raid/scratch/cyborg
#     DATADIR2=/raid/scratch/cyborg/SkynetData/Skynet_60
#     SCANNAME=2024_08_07_15
#     SRC_NAME=messier_101_10_sec_JLB
#     OBSERVER=socamrad_21318
#     DATE_OBS=2024-08-23T21:42:32.000
#        OBSID=120655
#      SCANNUM=70550
#          MJD=60545.904537
#          UTC=78152
#     SCANTYPE=onoff
#     DATAMODE=HIRES
#     RECEIVER=Rx1_2
#      OBSFREQ=1395.0000
# Actual_FREQ1=1419.0000,
# Actual_FREQ2=1419.0000
#    LO1Tuning=6869.0000
#     RFFILTER=1355_1435
#        OBSBW=-15.6250
#     EFFBANDW=15.6250
#        NCHAN=1024
#    STARTCHAN=51
```

```
#         TSYS=XX1:61.61, YY1:64.52
#         TSYS=XX2:61.64, YY2:64.51
#         TCAL=XX1:9.17, YY1:10.07
#         TCAL=XX2:9.17, YY2:10.07
# Calibrated spectra: Tsys*(ON-OFF)/OFF
#
#
#Freq1(MHz)         XX1          YY1    Freq2(MHz)       XX2
   1426.03430      -0.4742      -0.3980    1426.03430      -0.4
   1426.01904      -0.4654      -0.5037    1426.01904      -0.4
   1426.00378      -0.4724      -0.5247    1426.00378      -0.4
   1425.98853      -0.6686      -0.5503    1425.98853      -0.6
   1425.97327      -0.5241      -0.0985    1425.97327      -0.5
   1425.95801      -0.5196      -0.6789    1425.95801      -0.5
   1425.94275      -0.5562      -0.6868    1425.94275      -0.5
   1425.92749      -0.7655      -0.4898    1425.92749      -0.7
   1425.91223      -0.5528      -0.2995    1425.91223      -0.5
   1425.89697      -0.7900      -0.6677    1425.89697      -0.7
   1425.88171      -0.8184      -0.6903    1425.88171      -0.8
   1425.86646      -0.5768      -0.4041    1425.86646      -0.5
   1425.85120      -0.6430      -0.1667    1425.85120      -0.6
   1425.83594      -0.9532      -0.5836    1425.83594      -0.9
   1425.82068      -0.5565      -0.5983    1425.82068      -0.5
   1425.80542      -0.7361      -0.8664    1425.80542      -0.7
   1425.79016      -0.4358      -0.7937    1425.79016      -0.4
   1425.77490      -0.4988      -0.5952    1425.77490      -0.4
   1425.75964      -0.6343      -0.5919    1425.75964      -0.6
```

	B	C	D	E	F	G	H	I	J	K
1	Velocity	XX1	YY1	fitX	corX	fitY	corY	combined	smoothed	XL1
2	-1184.05	-0.4742	-0.398	-8.29E-01	0.354632	-8.10E-01	0.412428	0.38353	0.38353	2nd
3	-1180.85	-0.4654	-0.5037	-8.27E-01	0.361194	-8.09E-01	0.304809	0.333001	0.333001	0.00E+00
4	-1177.65	-0.4724	-0.5247	-8.24E-01	0.351955	-8.07E-01	0.28189	0.316923	0.347483	1st
5	-1174.45	-0.6686	-0.5503	-8.22E-01	0.153518	-8.05E-01	0.254373	0.203946	0.312775	0.0007
6	-1171.26	-0.5241	-0.0985	-8.20E-01	0.29578	-8.03E-01	0.704254	0.500017	0.283307	0th
7	-1168.06	-0.5196	-0.6789	-8.18E-01	0.298041	-8.01E-01	0.121935	0.209988	0.255408	0
8	-1164.86	-0.5562	-0.6868	-8.15E-01	0.259203	-7.99E-01	0.112117	0.18566	0.28999	YR1
9	-1161.66	-0.7655	-0.4898	-8.13E-01	0.047664	-7.97E-01	0.307198	0.177431	0.204401	2nd
10	-1158.46	-0.5528	-0.2995	-8.11E-01	0.258125	-7.95E-01	0.495579	0.376852	0.171302	0.00E+00
11	-1155.27	-0.79	-0.6677	-8.09E-01	0.018687	-7.93E-01	0.12546	0.072073	0.195433	1st
12	-1152.07	-0.8184	-0.6903	-8.06E-01	-0.01195	-7.91E-01	0.100941	0.044494	0.237915	0.0006
13	-1148.87	-0.5768	-0.4041	-8.04E-01	0.22741	-7.89E-01	0.385223	0.306317	0.167386	0th
14	-1145.67	-0.643	-0.1667	-8.02E-01	0.158971	-7.87E-01	0.620704	0.389838	0.195597	-0.1
15	-1142.48	-0.9532	-0.5836	-8.00E-01	-0.15347	-7.85E-01	0.201885	0.024209	0.184139	
16	-1139.28	-0.5565	-0.5983	-7.97E-01	0.240994	-7.84E-01	0.185266	0.21313	0.1572	
17	-1136.08	-0.7361	-0.8664	-7.95E-01	0.059155	-7.82E-01	-0.08475	-0.0128	0.126691	
18	-1132.88	-0.4358	-0.7937	-7.93E-01	0.357215	-7.80E-01	-0.01397	0.171621	0.155671	
19	-1129.68	-0.4988	-0.5952	-7.91E-01	0.291976	-7.78E-01	0.182608	0.237292	0.155462	
20	-1126.48	-0.6343	-0.5919	-7.89E-01	0.154237	-7.76E-01	0.183989	0.169113	0.198813	
21	-1123.28	-0.528	-0.6081	-7.86E-01	0.258298	-7.74E-01	0.16587	0.212084	0.209464	
22	-1120.09	-0.7282	-0.42	-7.84E-01	0.05586	-7.72E-01	0.352051	0.203956	0.209805	
23	-1116.89	-0.6292	-0.473	-7.82E-01	0.152621	-7.70E-01	0.297132	0.224876	0.189896	
24	-1113.69	-0.75	-0.3198	-7.80E-01	0.029581	-7.68E-01	0.448413	0.238997	0.180347	
25	-1110.49	-0.824	-0.5805	-7.77E-01	-0.04666	-7.66E-01	0.185793	0.069568	0.157737	
26	-1107.29	-0.6352	-0.5756	-7.75E-01	0.139902	-7.64E-01	0.188774	0.164338	0.125018	
27	-1104.09	-0.7916	-0.5619	-7.73E-01	-0.01874	-7.62E-01	0.200554	0.090908	0.085688	
28	-1100.89	-0.8031	-0.6055	-7.71E-01	-0.03248	-7.61E-01	0.155034	0.061279	0.090429	



m101 data | m101 analysis

I dump my data results into an excel spreadsheet to flatten the background and display the resulting spectrum in a nice plot with velocity on the x-axis instead of frequency.

There are templates and user guides for my analysis spreadsheets available.

References

1. https://en.wikipedia.org/wiki/Hydrogen_line
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3. Laurent Chemin, Claude Carignan and Tyler Foster – H I Kinematics and Dynamics of Messier 31 https://arxiv.org/pdf/0909.3846v1.pdf
4. S. Z. Kam, C. Carignan, L. Chemin, T. Foster, E. Elson, T. H. Jarrett – H I Kinematics and Mass Distribution of Messier 33 https://arxiv.org/pdf/1706.04248.pdf
5. https://en.wikipedia.org/wiki/Andromeda_Galaxy
6. https://en.wikipedia.org/wiki/Triangulum_Galaxy
7. https://en.wikipedia.org/wiki/Pinwheel_Galaxy
8. https://en.wikipedia.org/wiki/Messier_74
9. https://www.gb.nrao.edu/cgi-bin/radvelcalc.py