Starlink Verification and Dark Sector Lab RFI Measurements

DSL Spectrum Measurement

Version: 1.4

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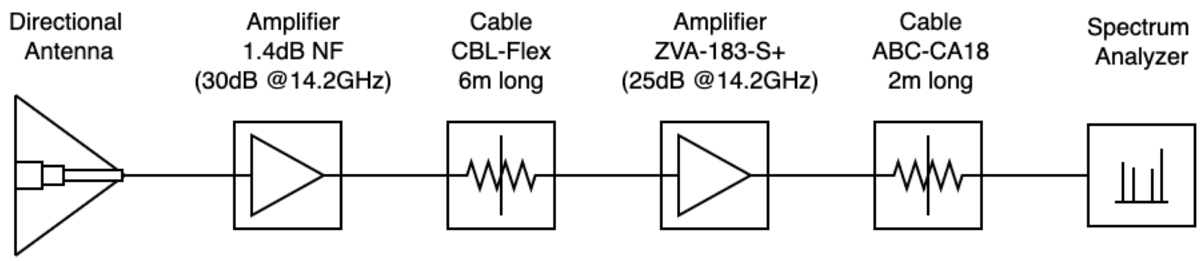
Table of Contents

The first half of this document summarizes Starlink testing between Dec 14 2022 and Jan 24 2023. It examines the link's impact on the RF spectrum measured from the Dark Sector Lab Building, and documents several mitigation strategies and their effectiveness.

1.0 Measurement Setup

A spectrum analyzer with directional feed horn antenna was set up in the Dark Sector on the roof of the Dark Sector Lab to record the local RF spectrum. The spectrum analyzer measures from 14 to 14.5 GHz with a resolution bandwidth of 3MHz. It operates a max hold function for 15 minutes, then saves the spectrum to disk.



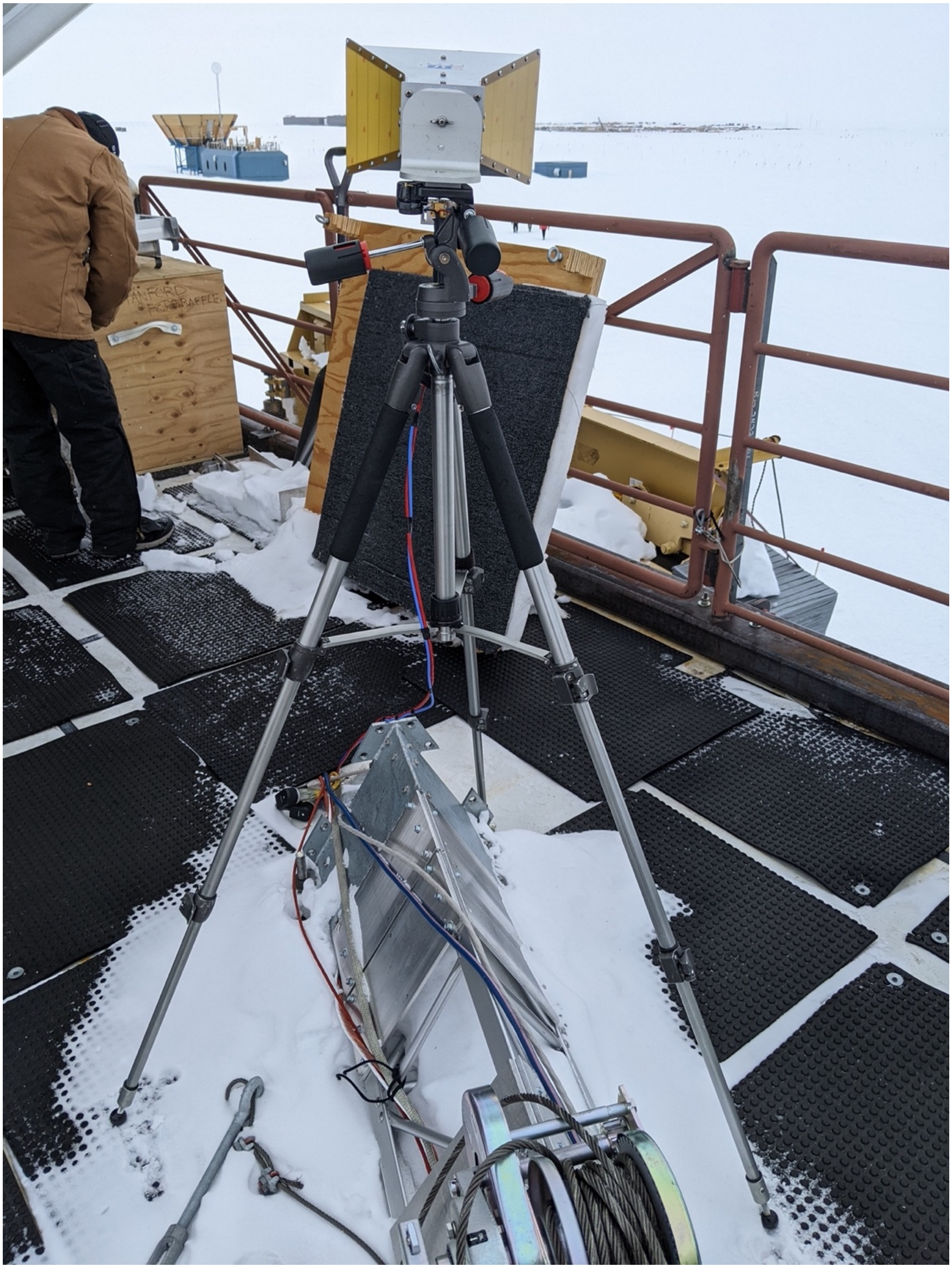
Above: Schematic diagram of the measurement setup. The first amplifier is mounted directly to the feed horn to minimize any attenuation before the first stage of amplification.

Description	Designation
Feed Horn	ETS Model: 3115
Amplifier 1	(30dB @14.2GHz, 1.4dB NF)
Cable	Mini Circuit CBL Flex 6 m length
Amplifier 2	Mini-Circuits ZVA-183-S+ (25dB @14.2GHz, 3.14dB NF)
Cable	AtlantecRF ABC-CA18-SMSM, 2 m length
Spectrum Analyzer	Anritsu MS2724B

Table: Components used for the measurement setup.

Description	Setting
Resolution	401 points
Center Frequency	14.248 GHz
Span	0.5 GHz
RBW	3 MHz
VBW	1 KHz
Sweep Time	≈ 866ms
Attenuator	0 dB
Trace Operation	max hold

Table: Spectrum Analyzer settings.



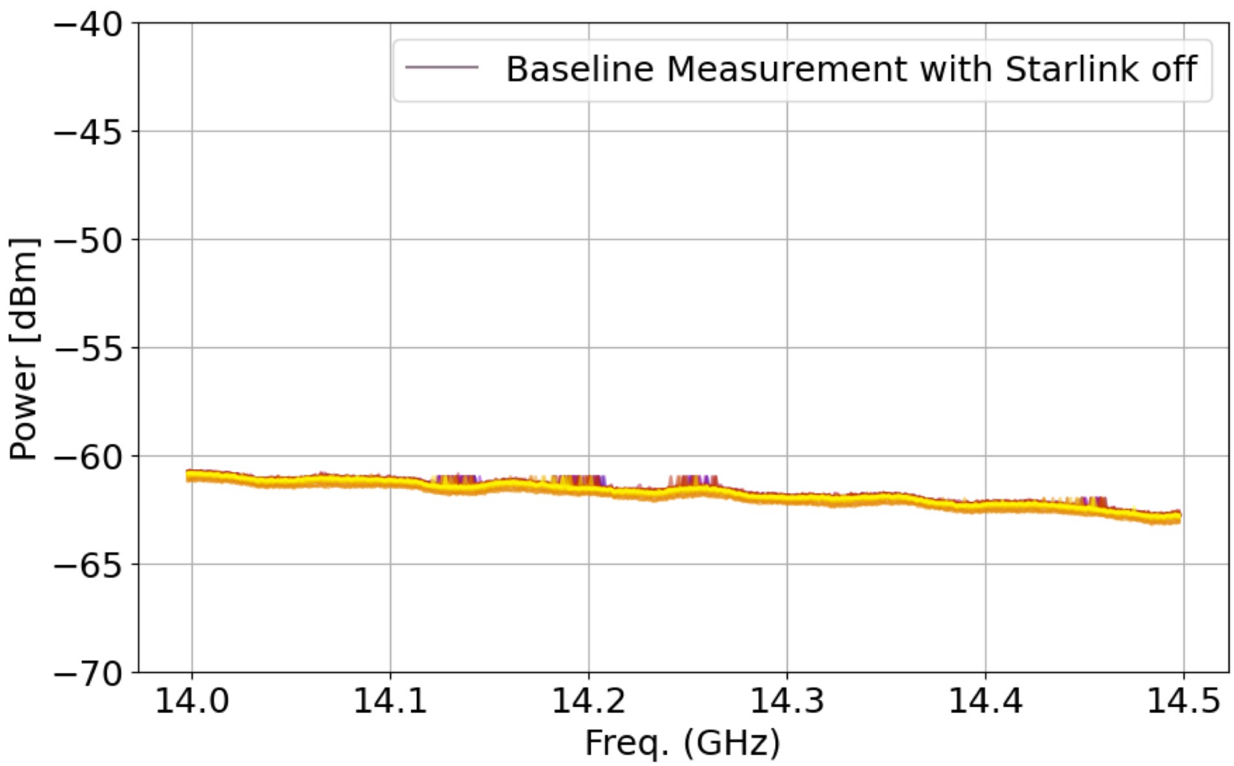
Above: picture of the feed horn measurement setup at DSL. Showing the feed horn pointing in the direction of SPRESSO.

2.0 Data Analysis

We began recording spectra on Dec 15, after the Starlink antenna was moved to the roof of the building in the RF sector, and continued recording spectra since then. This allowed us to compare the spectral contents for different orientations and mitigation configurations, like the installation of the absorber panels.

The raw spectra are saved in daily ".csv" files containing 96 individual 15 min max hold traces. Notice, that the Starlink transmission is not constant and varies throughout the day depending on which satellites the antenna connects to and which frequency band it uses. Therefore, the spectral power changes as a function of frequency and as a function of time, making it difficult to discern individual spectra effectively. However, comparing the average detected power between days is consistent enough to compare different Starlink antenna configurations.

An example plot of the measured spectrum without the Starlink antenna transmitting is shown below. The plot shows all recorded spectra from a single day, with yellower colours indicating a later time of day. The data was collected on Dec 21, 2022. Note, that the spectrum in this case shows the noise floor of the measurement setup, hence we are not able to detect any signals below this level. We have also seen some quantization readout artifacts, most of them are within 0.5dB and always peak in groups at the same level.



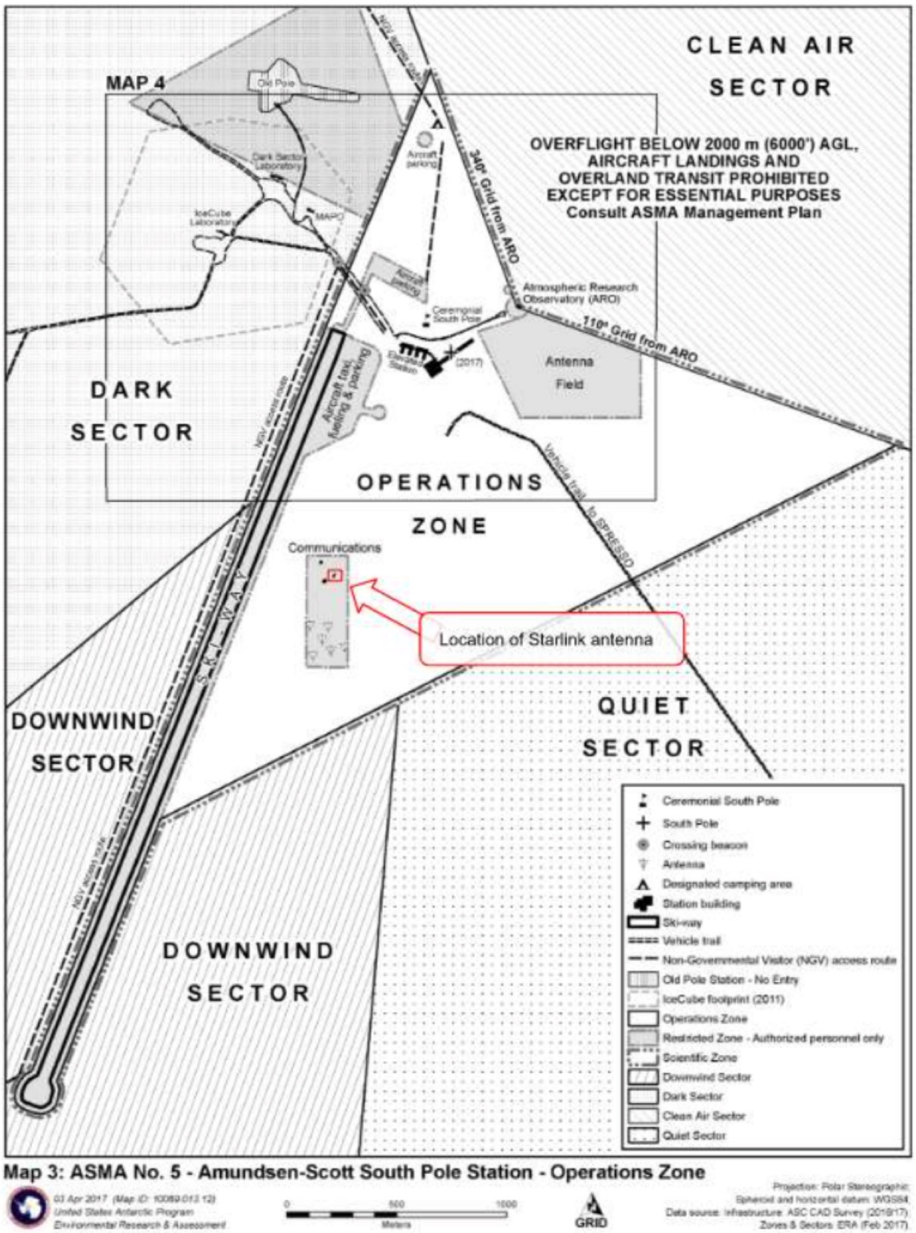
Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. (Date: Dec 21, 2022)

3.0 Results

For this report we focus on one day of data for each configuration. Each section contains a picture of the setup, a 24-hour spectra, and a Starlink connectivity plot extracted from the IceCube Grafana monitor.

The spectra are plotted with identical axis and therefore can be compared directly. We also included two maps pointing out the location of the Starlink antenna in the RF Sector and at SPRESSO.

3.1 RF Sector antenna location

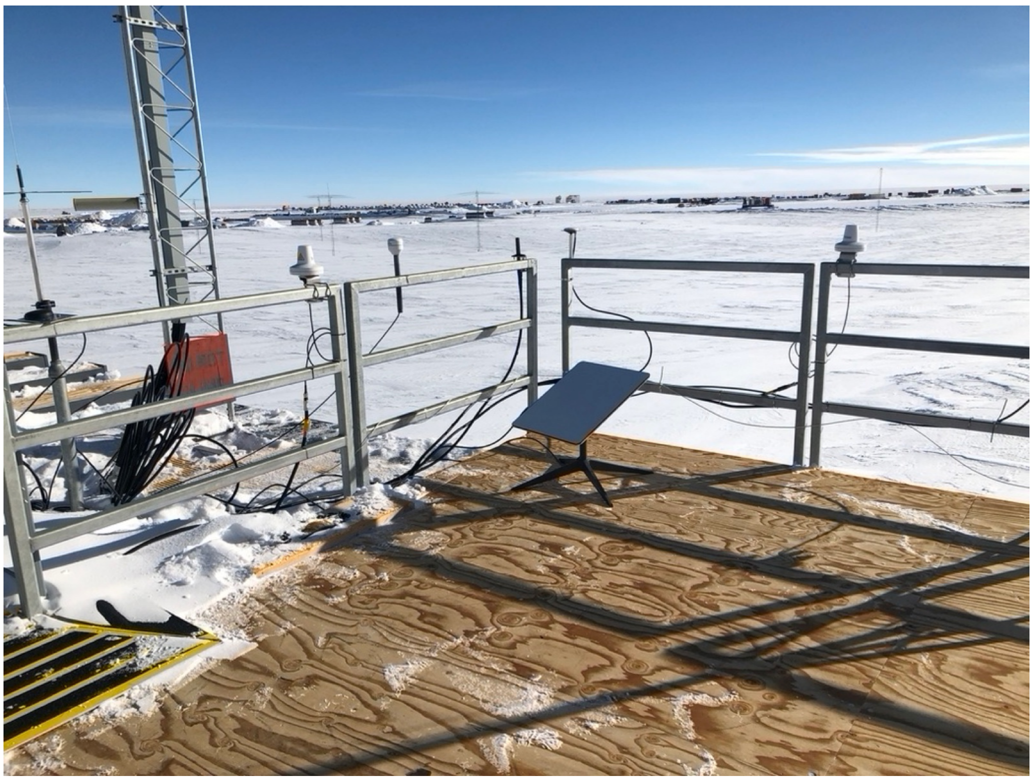


Above: image from the South Pole Station intranet, with the location of the Starlink antenna marked in red.

3.1.1 Configuration 1: RF Sector location without absorber

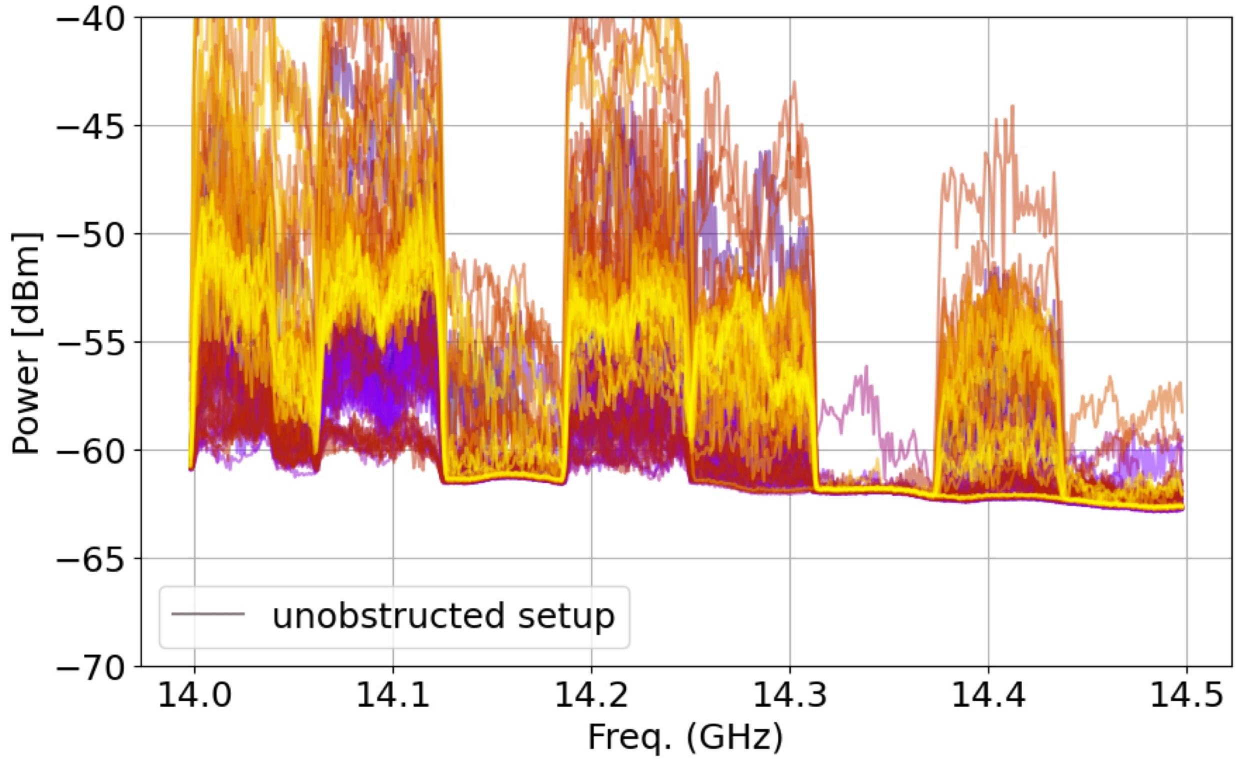
For the first configuration we placed the Starlink antenna on the roof of the RF building to minimize obstructions. The antenna was also mounted with the original tripod, which allowed it to move freely. After the initial setup the antenna settled at an elevation of about 60 deg and an azimuth direction of grid North-West towards the Dark Sector. After the antenna initially orientated itself, we could not observe any further movement for the couple of days we took data in that configuration.

The data used for this configuration was taken during the following period: Dec 14-16, 2022.



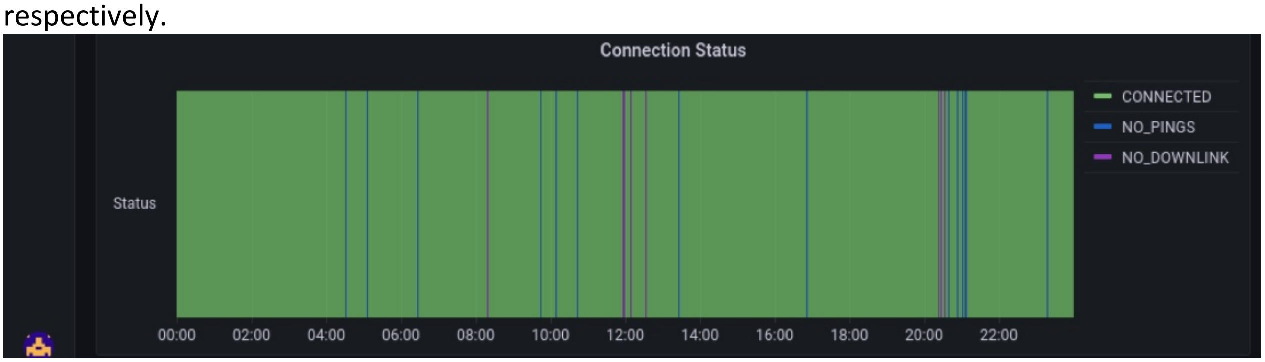
Above: shows the Starlink antenna installed on the roof of the RF sector building, pointing towards the Dark Sector.

The measured spectra for a day in this configuration is shown in the plot below. Comparing this plot with the base line plot from the previous section, we can see that for most of the Starlink frequency bands the power level is about 15 to 20 dB above the noise floor. Again, each color represents 15 min max hold spectra, where more yellow colours indicate a later time.



Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. (Date: Dec 15, 2022)

The other metrics that we look at for our tests is the connectivity of the Starlink terminal. Basically, what is the percentage of the terminal reporting that it established a link with a satellite. This metric is recorded from the Starlink service data and is visualized with Grafana. For this configuration we have about 99 percent connectivity in a 24 hour window. There are only a few instances where we did not get a ping, or no downlink, marked in blue and purple, respectively.



Above: Shows the connectivity data for the Starlink terminal, green indicates connected. (about 99 percent connected)

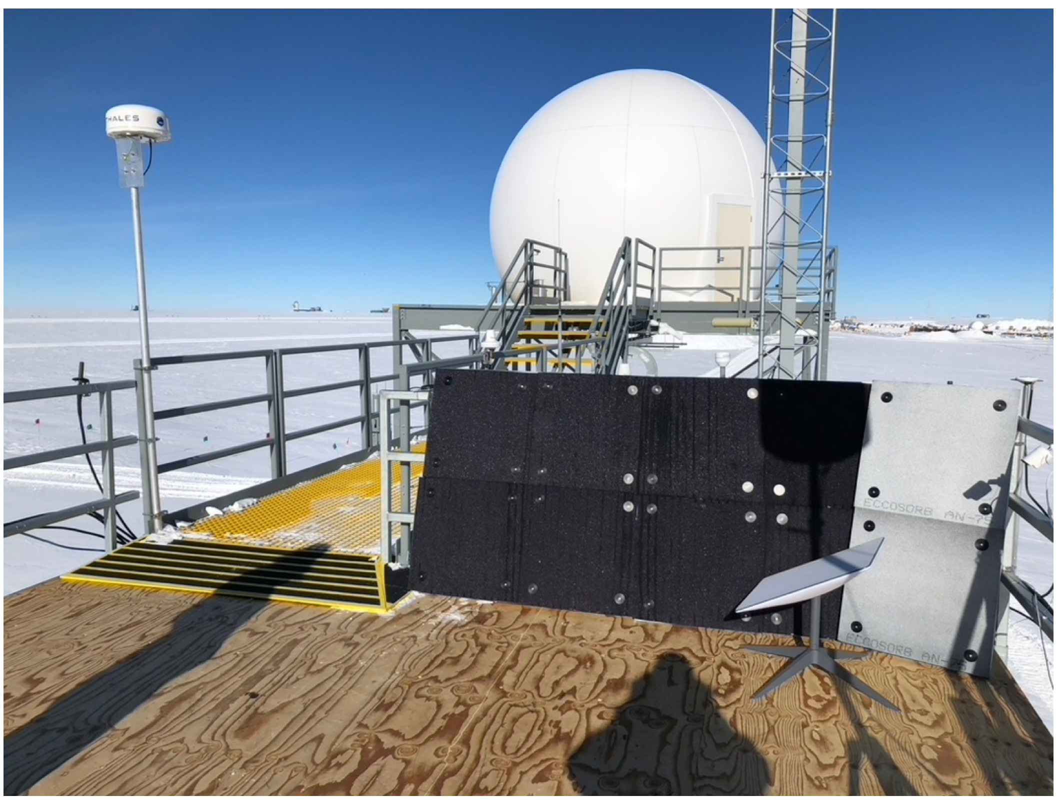
3.1.2 Configuration 2: RF Sector location with absorber

For this configuration we placed absorber panels in the line of sight of the Dark Sector.
The panels consist of plywood - metal - echosorb foam. The metal acts as a reflector, and the foam is an RF attenuator. Signals sent in the direction of the panels are attenuated once as they enter the foam, then are reflected by the metal, and attenuated again as they exit.
There are three panels:

- 2x 4’x4’ with approx. -10dB foam (black)
- 1x 2’x4’ with approx. -20dB foam (white)

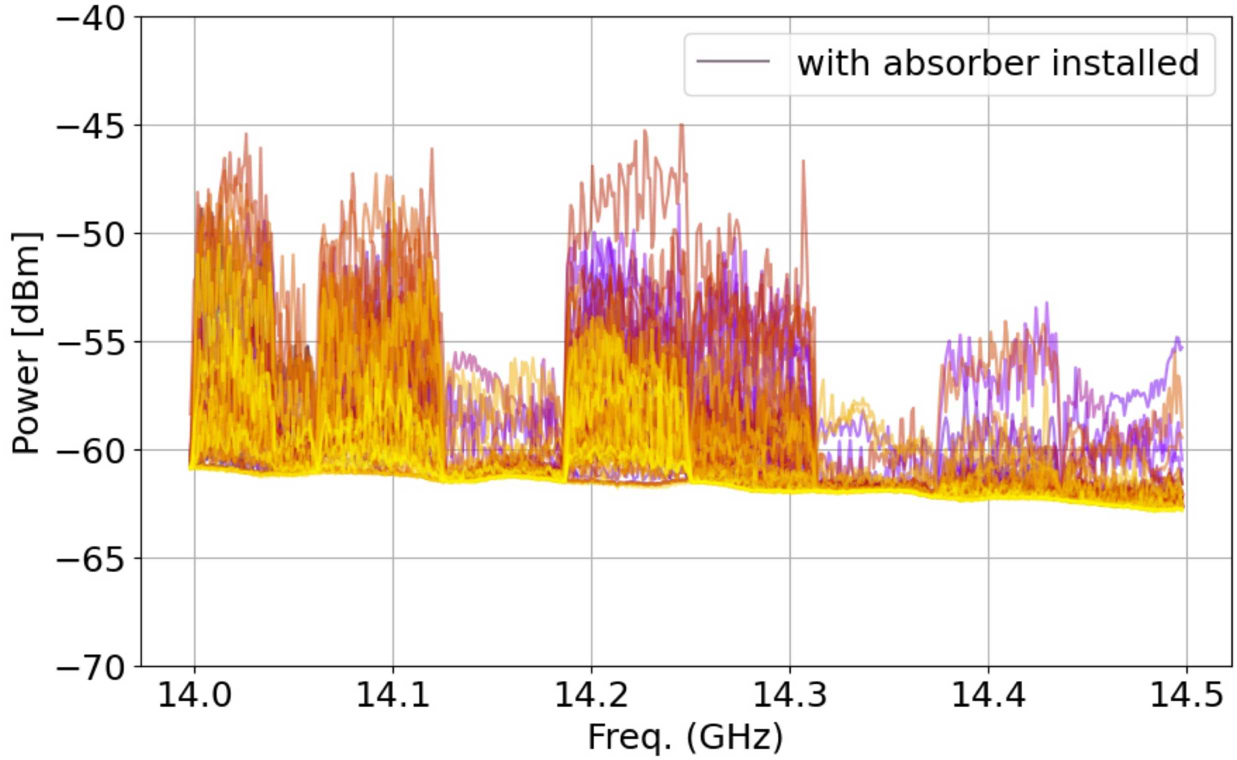
The Starlink antenna was kept in the same location and orientation. Thereby allowing us to compare the effect of the absorber panels without changing any other parameter in the test setup.

The data used for this configuration was taken during the following period: Dec 16-20, 2022.



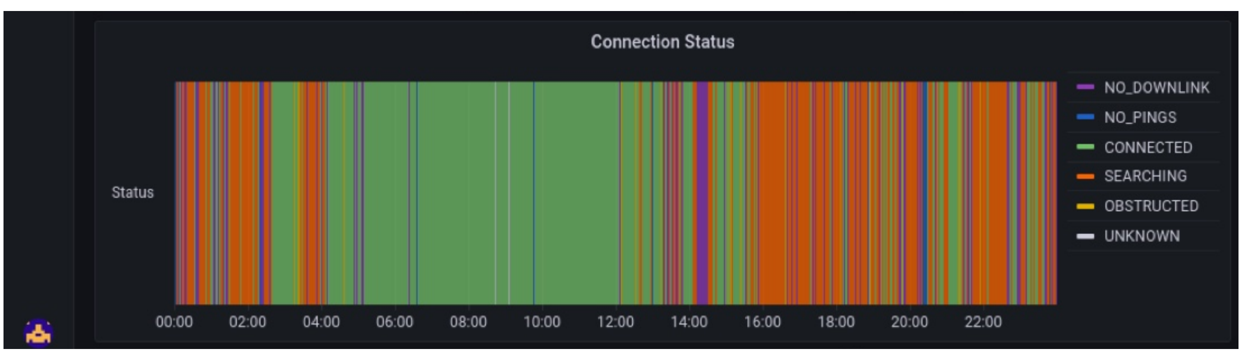
Above: panels temporarily installed in the RF sector, adjacent to the antenna. The dark sector is visible in the background to the left of the white dome.

The spectra for this configuration showed a decrease of about 10dB compared to the measurement without the absorber panels present. However, even with shielding the Starlink antenna with absorber panels we still can see the signal clearly.



Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. (Date: Dec 17, 2022)

Looking at the connectivity data for this configuration we can see that the absorber panels significantly impact the ability to establish a link with the satellite. With this configuration the antenna achieves about 84 percent connectivity.



Above: Shows the connectivity data for the Starlink terminal, green indicates connected. (about 84 percent connected)

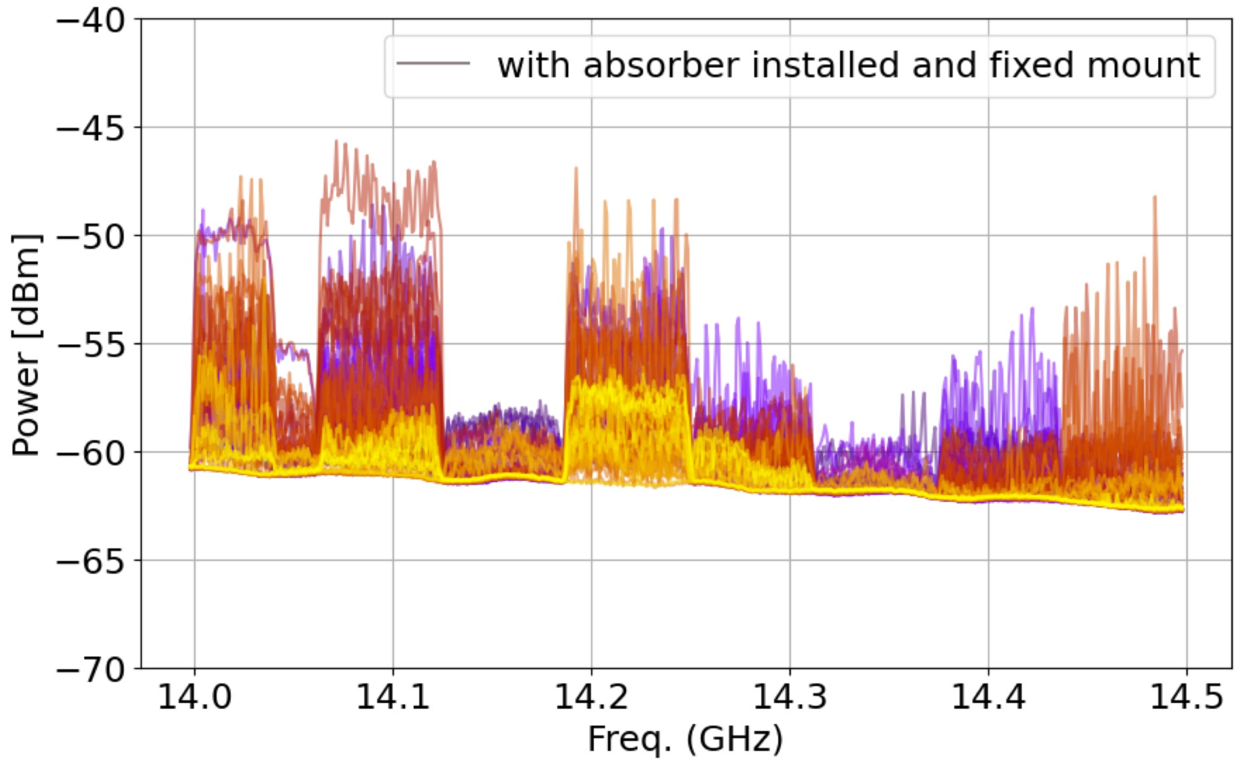
3.1.3 Configuration 3: RF Sector location with absorber and fixed mount

For this configuration we mounted the Starlink antenna in a frame that prevents it from moving freely, thereby allowing us to set the elevation and azimuth pointing. With the antenna motion deactivated, we pointed the antenna at the same elevation as it used to point when it was free moving, 60 deg elevation, and set the azimuth direction to be grid South-East, pointing it in the opposite direction of the Dark Sector.

The data used for this configuration was taken during the following period: Dec 26-28, 2022.

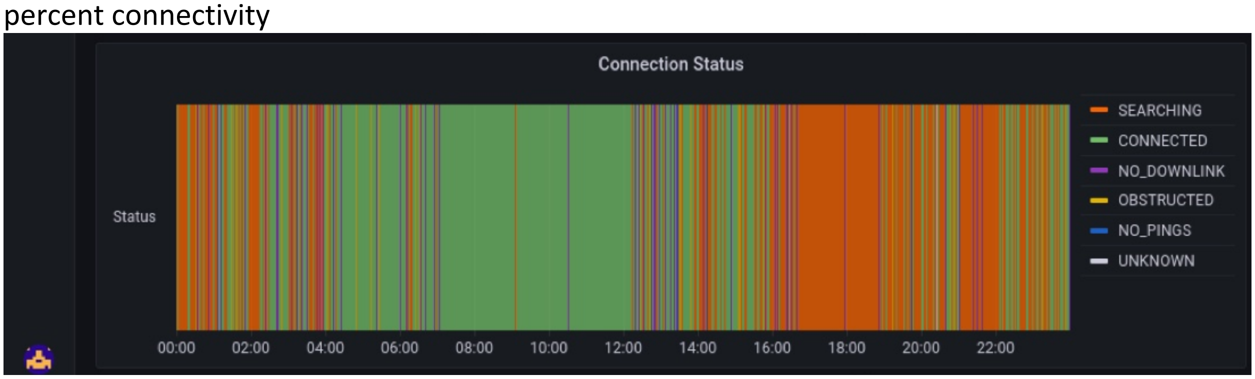
Above: Starlink antenna mounted in a frame that prevents it from moving freely. The picture shows it pointing approximately 60 deg in elevation and South-East in azimuth.

The spectra for this configuration looks similar to the one shown in configuration two where the antenna was pointing towards the Dark Sector. This measurement shows that even by physically changing the antenna orientation while keeping it at the same location does not lead to significant reduction in signal strength as seen from the Dark Sector. The beamforming capabilities of the Starlink antenna counteract any physical orientation change and lead to similar interference levels regardless of its primary orientation.



Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. (Date: Dec 27, 2022)

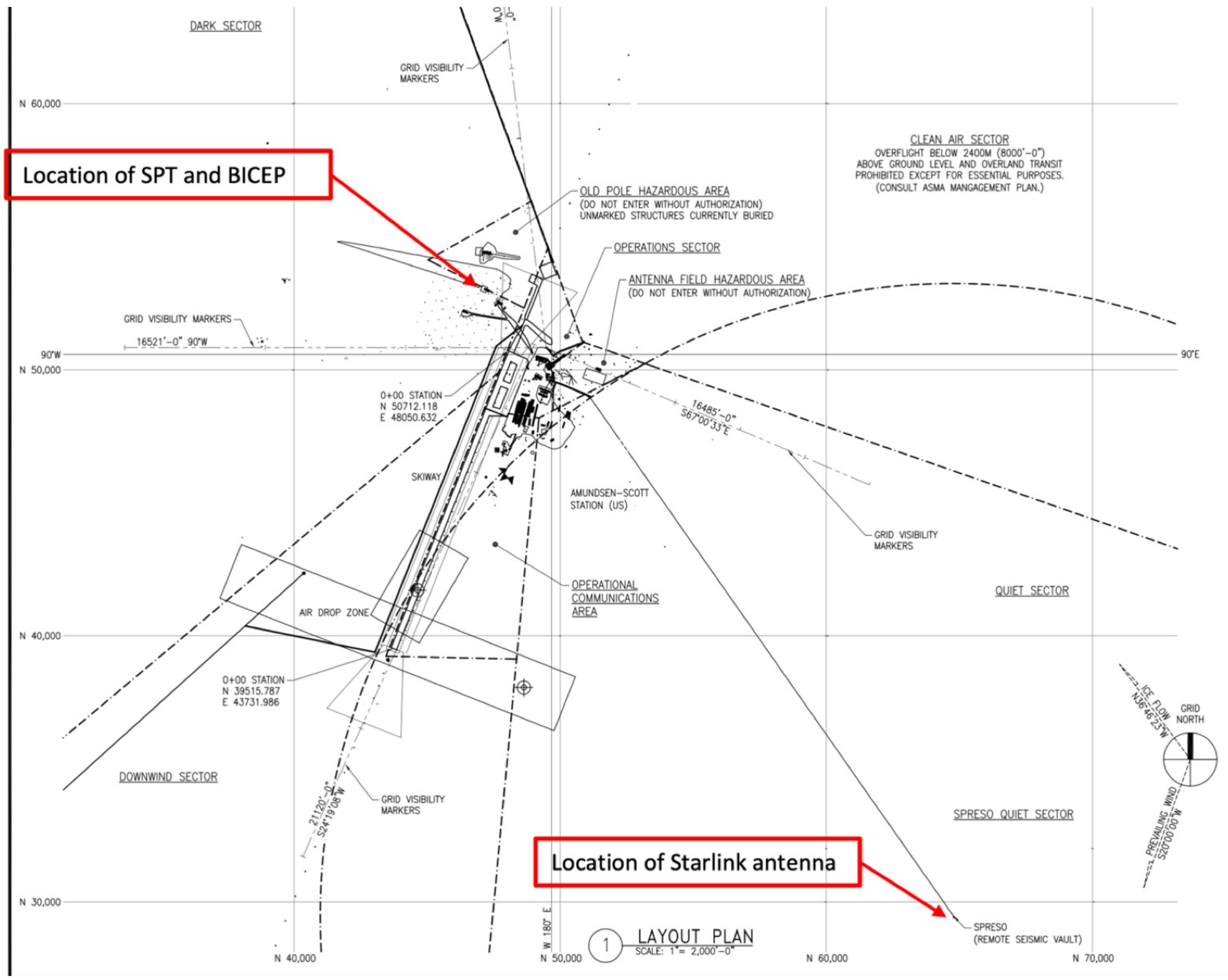
The connectivity data for this configuration shows and even worse ability of the antenna to establish a link with the satellite. With this configuration the antenna achieves about 70 percent connectivity



Above: Shows the connectivity measurement for the Starlink terminal, green indicates connected. (about 70 percent connected)

3.2 SPRESSO location

For the next set of configurations we moved the Starlink antenna to the SPRESSO location in the Quiet Sector. The antenna location is approximately 10 km away from DSL in the grid South-East direction. There are two tests planned for this location, first using the frame to set the pointing of the antenna to zenith and second allowing the antenna to free move with the original tripod.
The location of the Starlink antenna and the Dark Sector Lab is shown in the map below and indicated by the red arrows.

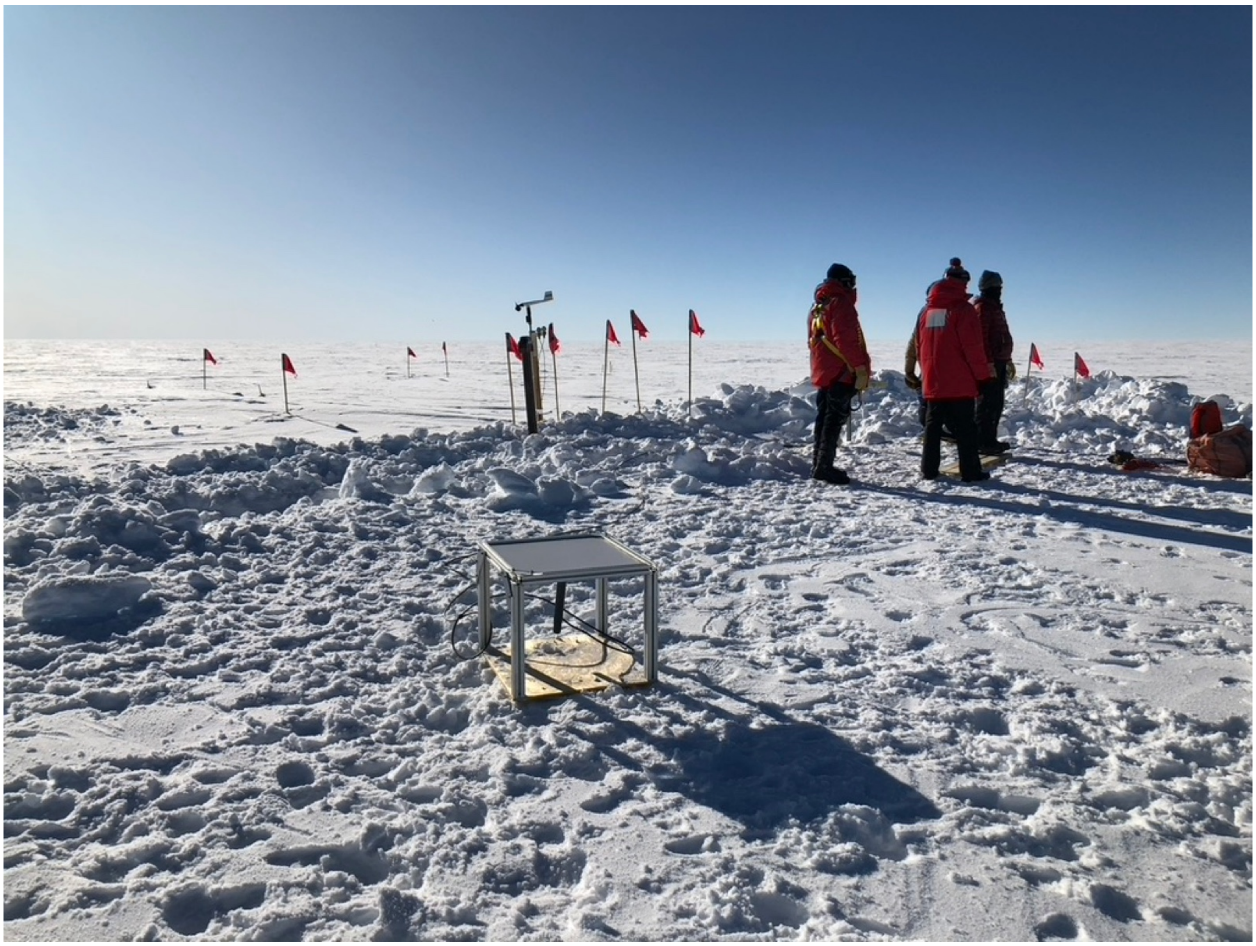


Above: image from the South Pole Station intranet, with the location of the Starlink antenna and the DSL. Distance between SL and DSL is approximately 10km.

3.2.1 Configuration 4: SPRESSO location pointing to zenith

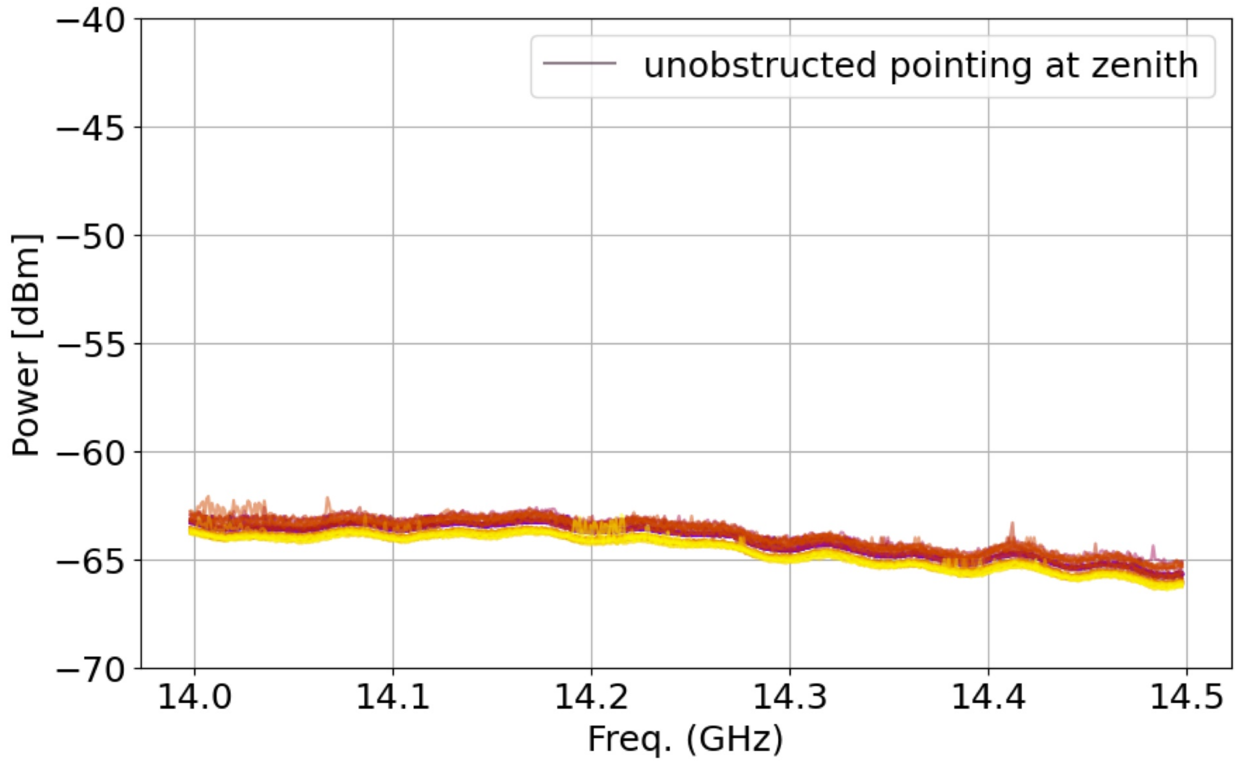
For this configuration we placed the Starlink antenna in the mounting frame and located it on the ground at approximately 7m distance from the SPRESSO instrumentation vault. See picture below.

Antenna installed at SPRESSO in fixed frame, pointing to zenith (Jan 17-24)



Above: Starlink antenna temporarily installed at SPRESSO. The flags in the center mark the hatch to the instrumentation vault.

To measure the spectra for this configuration we realigned the measurement setup to point in the direction of SPRESSO. This changed the baseline level to a slightly lower value compared to the original baseline presented in the Data Section. Significant here is that we can barely see the Starlink transmission in the spectra. There are only a few occasions where the signal is slightly above the noise floor. This is so far the most promising configuration and shows an effective approach to minimizing the impact of Starlink at the Dark Sector.



Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. (Date: Jan 21, 2023)

Furthermore, the connectivity of this configuration shows a nearly 100 percent ability of the Starlink terminal to establish a link to the satellite. Note that this plot shows the connectivity for the last seven days of testing.

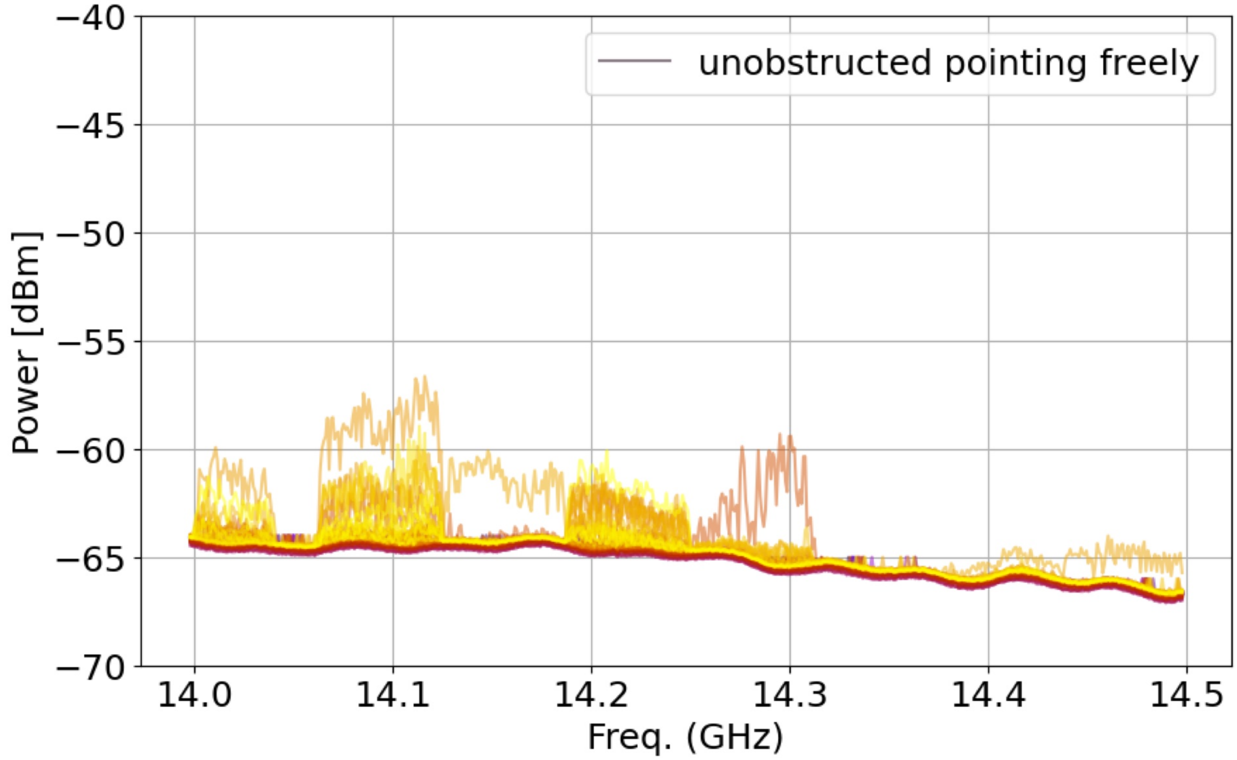
Above: Shows the connectivity measurement for the Starlink terminal, green indicates connected. (about 100 percent connected)

3.2.2 Configuration 5: SPRESSO location pointing freely

For this configuration we removed the fixed antenna mount and installed the Starlink antenna on its factory pole mount. The pole mount allows the antenna to freely move and point to its preferred direction. After powering up the antenna it orientated itself to grid North-West, same orientation as when it was installed at the RF sector.

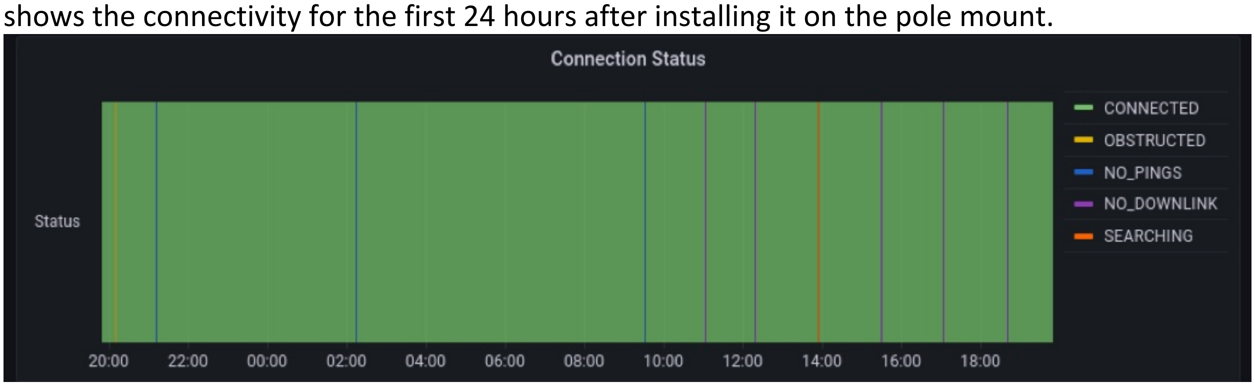
Above: Starlink antenna installed on the factory pole mount. With this configuration the antenna can freely move.

With the antenna pointing in the grid North-West direction we were able to pick up the the uplink above the noise floor again. From the first 24 hours of data, we can see that the signal strength is about 5 dB above the noise floor. This result is still significant better than any other configuration from the RF Sector. Our theory is that with the antenna being able to tilt to a lower elevation, it can beamform to satellites closer to the horizon and therefore transmissions going towards the direction of the Dark Sector can be low enough in elevation, so that the DSL might be in the primary beam.



Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. (Date: Jan 30, 2023)

The connectivity of this configuration nearly 100 percent. There are some short 1-2 min drops when Starlink moves the antenna to point to zenith for searching operation. Note that this plot shows the connectivity for the first 24 hours after installing it on the pole mount.



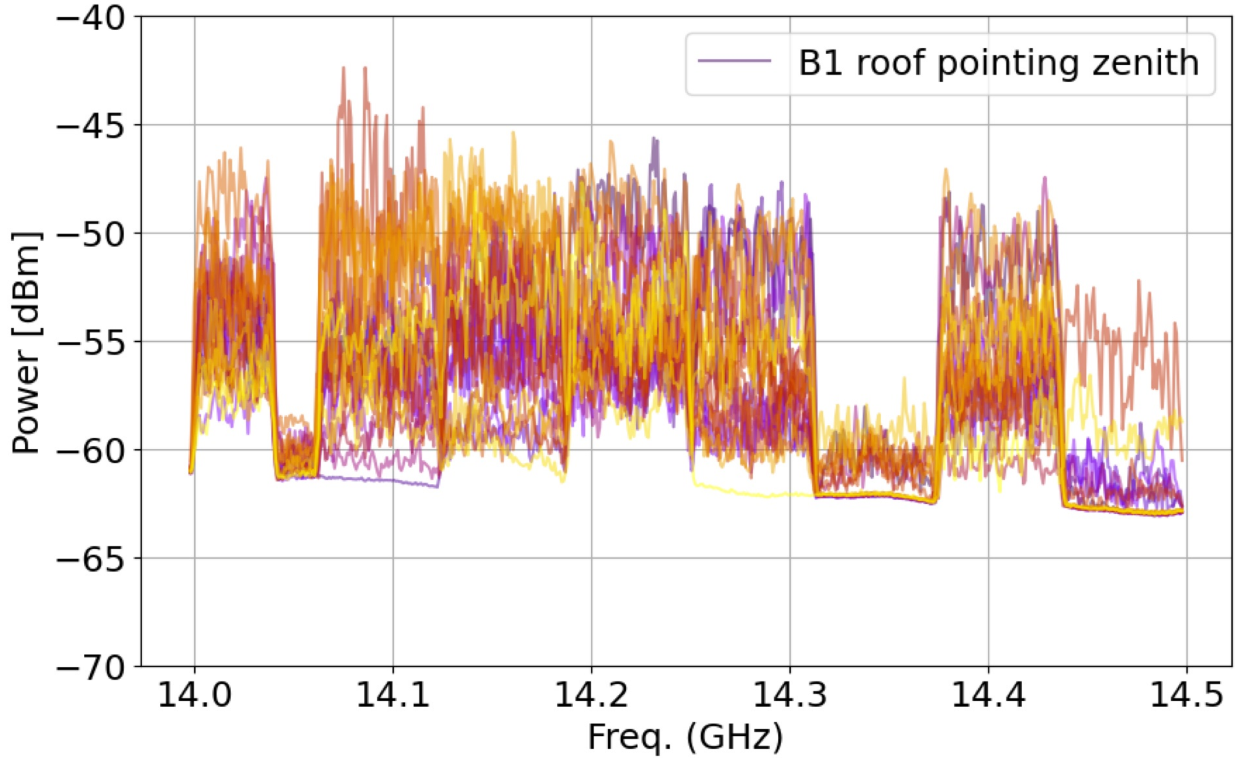
Above: Shows the connectivity measurement for the Starlink terminal, for the free moving configuration, green indicates connected. (about 100 percent connected)

3.3 B1 station roof location

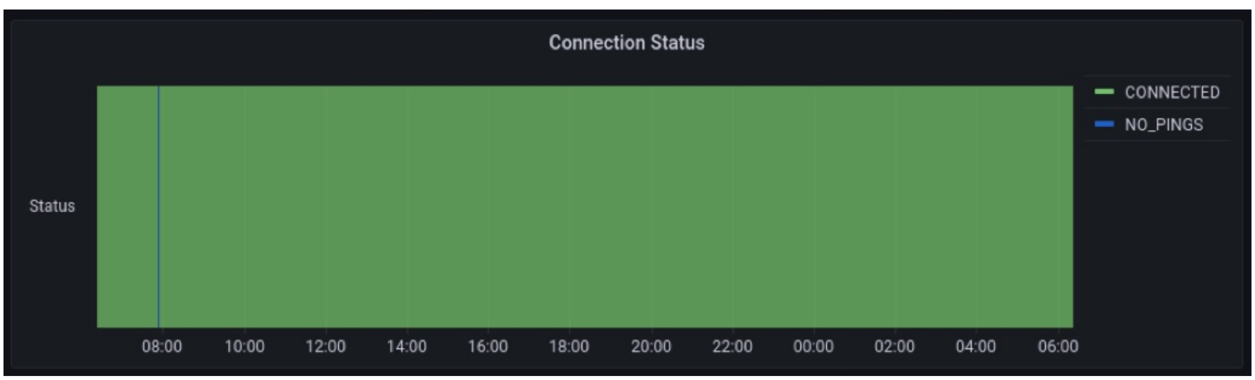
This is the last test location we have planned to operate the antenna in the summer season 2022/2023. The location was chosen, because it is the only one on site where we have the infrastructure in place and also has no line of sight to the Sark Sector. The roof of B1 has an already existing cable feed through to the emergency comms room. We used this existing hole to setup the modified Starlink antenna with the new Styrofoam cover. Firstly, we wanted to test how the antenna performs thermally and connectivity wise with the Styrofoam cover present. Secondly, we wanted to test if this location provides better shielding compared to the RF Sector location.

Above: Starlink antenna installed on the roof of the B1 wing of the elevated station. The antenna motor is deactivated and pointing at zenith. Also a Styrofoam cover is installed for temperature insulation.

Based on the measured spectra shown below, we can see that the Starlink antenna transmission from the roof of B1 causes similar RFI in the Dark Sector as when the antenna is located at RF and shielded with the absorber panels. See configuration 3.1.2 for comparison. However, in this configuration we have nearly 100 percent connectivity. This indicates that with additional shielding, installing the panels, we could see lower interference than any past configuration at the RF Sector.



Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. (Date: Feb 08, 2023)



Above: Shows the connectivity measurement for the Starlink terminal when located at the B1 roof. Green indicates connected. (about 100 percent connected)

4 Other RFI in the Dark Sector

In this section we focus on other RFI sources seen in the Dark Sector. We focus on a number of known transmitters on station as well as provide a wideband frequency sweep from 1GHz to 16GHz.

4.1 Adjusted Measurement Setup

For this set of measurements, we removed the directional feed horn and replaced it with an omni-directional antenna. The rest of the measurement setup remained the same. Based on the data sheet of the previously used feed horn we can approximate the difference in antenna gain between those two setups. The “ETS Model: 3115” feed horn has an antenna gain of approximately 10dBi, compared to the omni-directional antenna (0dBi). So, if we want to compare the measurement results for the Starlink tests above with the measurement results in this section, we only need to add approx. 10dB to the plots in this section. Or subtract 10dB of the Starlink plots to compare it to the omni-directional ones.

Above: picture of the omni-directional feed measurement setup at DSL.

Description	Designation
Feed	A.H. Systems SAS-547 1 GHz to 18 GHz
Amplifier 1	(30dB @14.2GHz, 1.4dB NF)
Cable	Mini Circuit CBL Flex 6 m length
Amplifier 2	Mini-Circuits ZVA-183-S+ (25dB @14.2GHz, 3.14dB NF)
Cable	AtlantecRF ABC-CA18-SMSM, 2 m length
Spectrum Analyzer	Anritsu MS2724B

Table: Components used for the omni-directional measurement setup.

Description	Setting
Resolution	401 points
Center Frequency	Variable
Span	Variable
RBW	3 MHz
VBW	1 KHz
Sweep Time	Variable
Attenuator	0 dB
Trace Operation	max hold

Table: Spectrum Analyzer settings.

Note, that we used different spectrum analyzer setups for this section. The parameters that we changed was the center frequency and the span (bandwidth), however the remaining parameters stayed the same. We still used the “max hold” trace operation and collected the spectrum for 15 minutes. After which we saved it to disk and restarted the max hold operation.

4.2 Satellite internet transmissions (SPTR, DSCS, Skynet)

In this section we focus on the known satellite internet transmissions from the RF Sector. There are three different satellites that the South Pole Station uses for internet connectivity, SPTR, DSCS, and Skynet. Skynet and DSCS are operating around 8GHz, whereas SPTR operates at a similar frequency to Starlink, around 15GHz.

4.2.1 DSCS and Skynet

Here are the technical information for DSCS, note that the orientation of the DSCS antenna was changed in 2022 from B7 (104E) to B13.

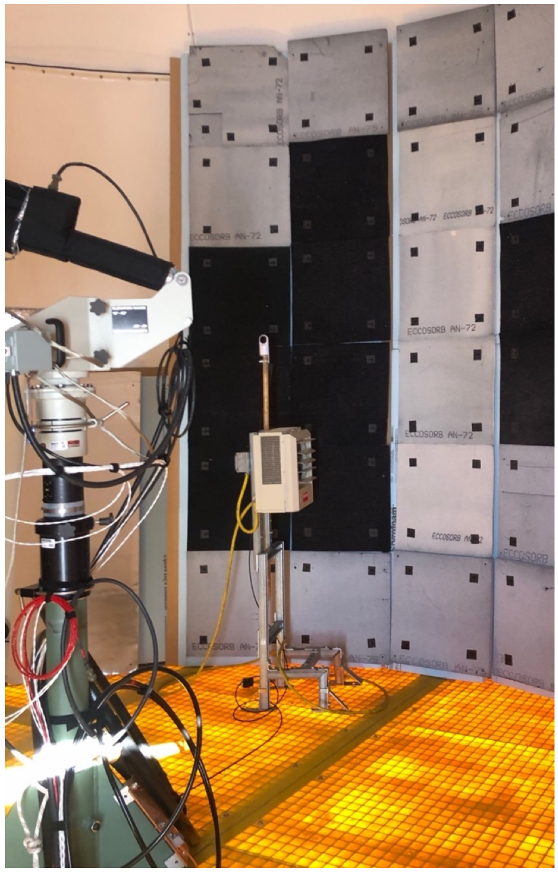
- Rx Freq: 7287.5 MHz
- Tx Freq: 8302.5 MHz
- EIRP: approx. 60.4 dBW

- DSCS B13 (current, active satellite we use day-to-day):
    - Azimuth Angles during transmit: 246.7 to 248.2 degrees (measured)
    - Elevation Angles during transmit: -0.5 to 1.7 degree (measured)

- DSCS B8 (Testing Only at the moment):
    - Azimuth Angles during transmit: 179.76 to 180.52 degrees (calculated)
    - Elevation Angles during transmit: 0 to 1.26 degrees (calculated)

- DSCS B11 (Testing Only at the moment):
    - Azimuth Angles during transmit: 134.15 to 134.76 degrees (calculated)
    - Elevation Angles during transmit: 0 to 0.84 degrees (calculated)

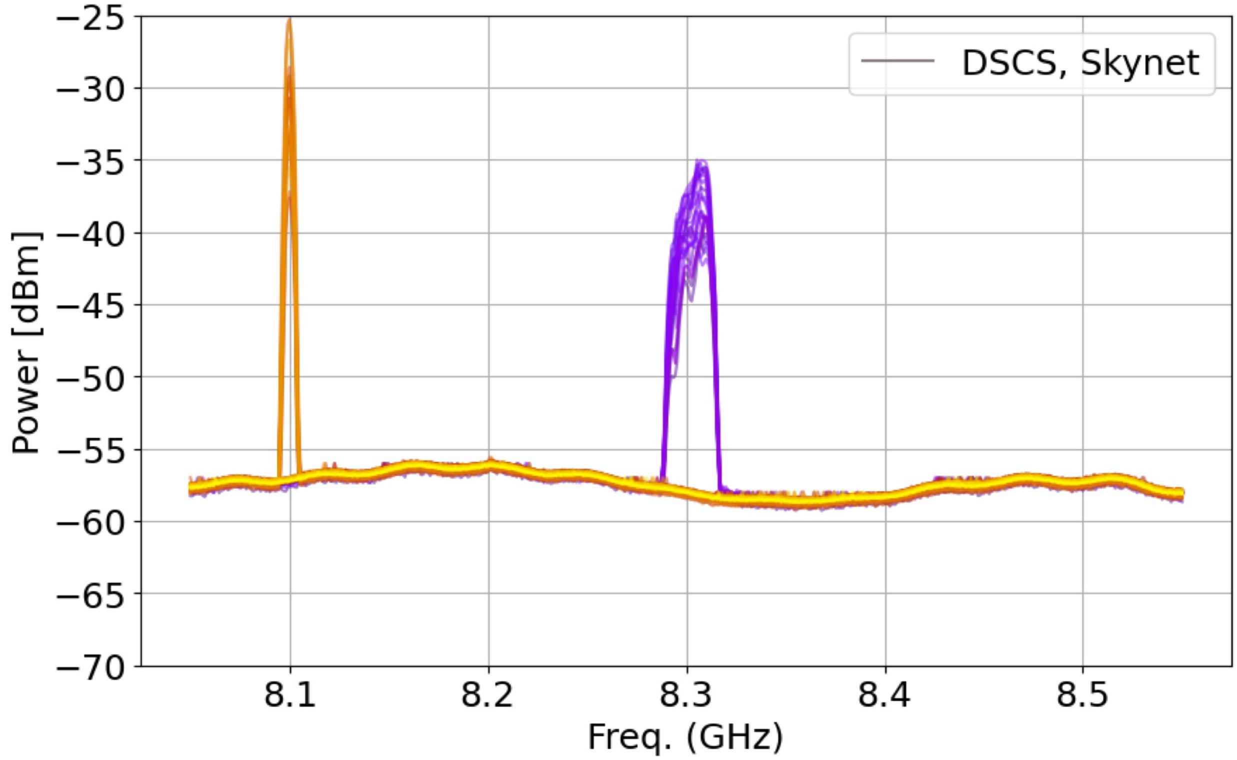
The RF dome, which houses the DSCS antenna has also an absorber wall installed, which is used to attenuate the signal emitted in the direction of the Dark Sector. A picture of the inside of the dome showing the absorber wall is shown below. Note, that when we inspected the dome in the summer 2022-2023 season, we noticed that the absorber wall in not in line of sight to the Dark Sector. This is most likely because the orientation of the DSCS antenna was changed from B7 to now B13.


Above: picture of the DSCS RF dome, one can see the absorber wall behind the antenna mount.

The technical information for Skynet are:

- Rx Freq: 7275 MHz
- Tx Freq: 8100 MHz
- EIRP: approx. 60.0 dBW
- Azimuth Angles during transmit: 32.4 to 35.0 degrees (measured)
- Elevation Angles during transmit: 0.00 to 6.25 degrees (measured)

To measure the RFI caused by DSCS and Skynet, we set the spectrum analyzer to a center frequency of 8.3 GHz and a span of 500MHz. This allows us to measure both satellite transmissions within one spectrum. The plot below shows the spectra for a 24-hour period identical to the ones we used for the Starlink verifications. One can see the two satellite transmissions, DSCS at approx. 8.3GHz and Skynet at 8.1GHz. Note, that the color of the trace indicates the time of the transmission within the 24-hour period. The darker color indicates an earlier time and the brighter color a later time of the day. DSCS transmits for approximately 5 hours per day and Skynet for approximately 6 hours per day.



Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. (Date: March 16, 2023)

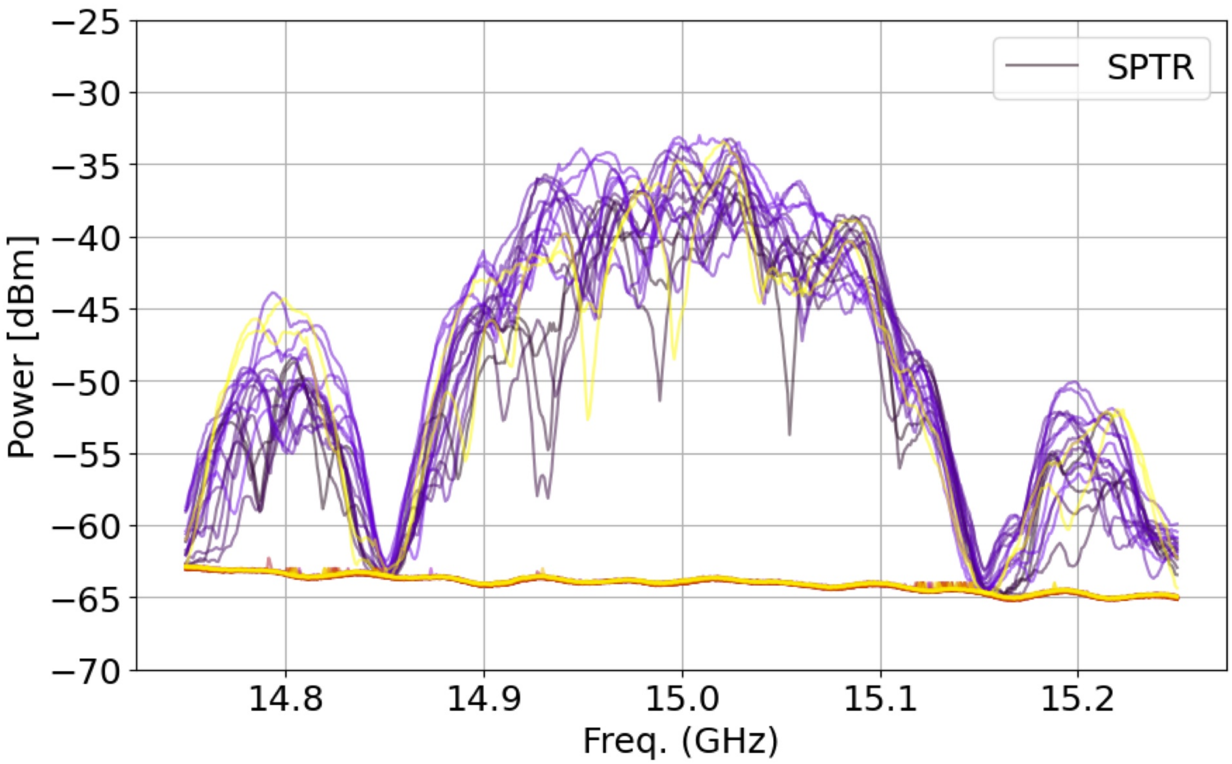
Based on the measurement, one can see that both transmissions are narrower in bandwidth compared to the Starlink transmissions. When looking at the total power one can see that the signal level is much higher compared to most of the Starlink configurations seen in Section 3. Again, when comparing the power level between the Starlink measurements with the directional feed horn and the other RFI measurements in this section, one must add 10dB to this plot.

It would be interesting to explore, if the DSCS signal strength can be further attenuated by rearranging the absorber wall in its RF dome.

4.2.2 SPTR

The SPTR transmissions are easier to compare to Starlink, as they are similar in frequency and bandwidth. The technical specifications for SPTR are:

- Rx Freq: 13775 MHz
- Tx Freq: 15003.4 MHz
- EIRP: 69.3 dBW
- Azimuth Angles during transmit: 313.2 to 314.77 degrees (calculated for the full SPTR pass, whereas we are only active approximately 70% of the visible window)
- Elevation Angles during transmit: 0 to 5.7 degrees (calculated for the full SPTR pass, whereas we are only active approximately 70% of the visible window)

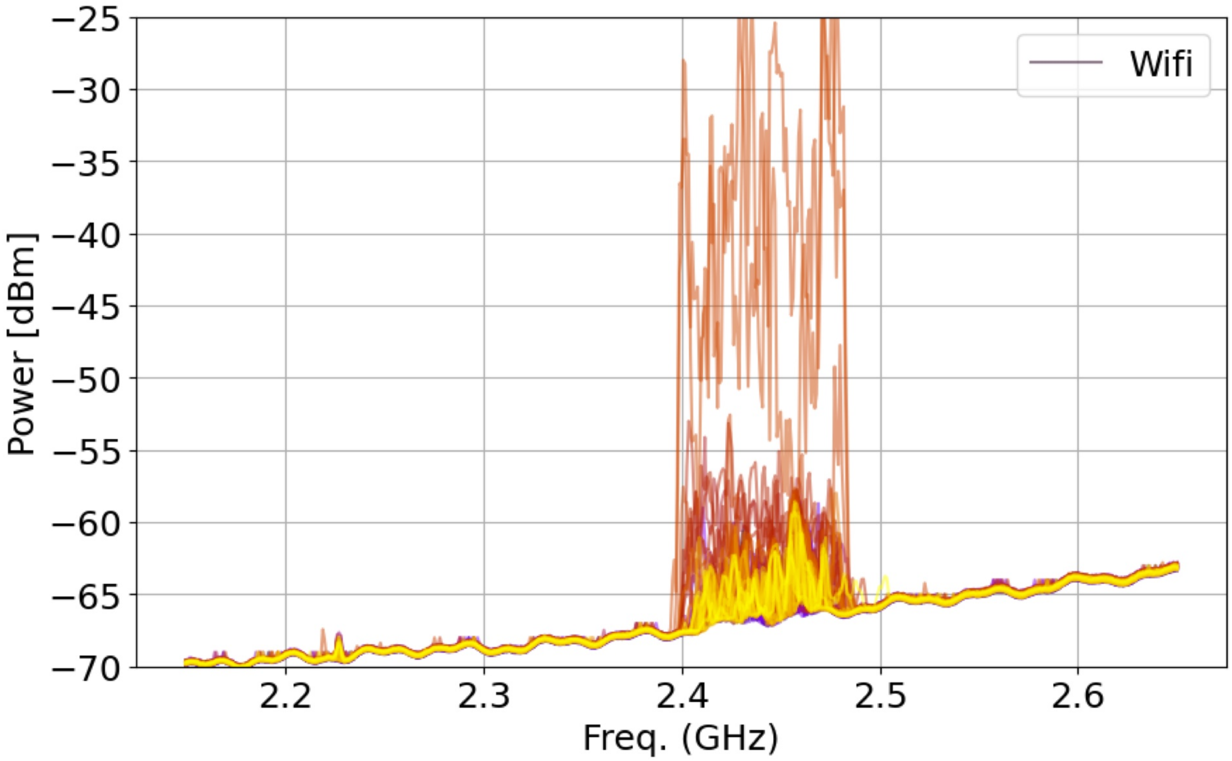


Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. (Date: Feb 15, 2023)

When comparing the SPTR transmission with the Starlink transmissions in Section 3, one can see that the occupied bandwidth is very similar, however the shape of the bandpass looks very different for Starlink. The adjusted signal level (with 10dB added) is with about -35dBm still higher compared to all Starlink configurations that we tested.

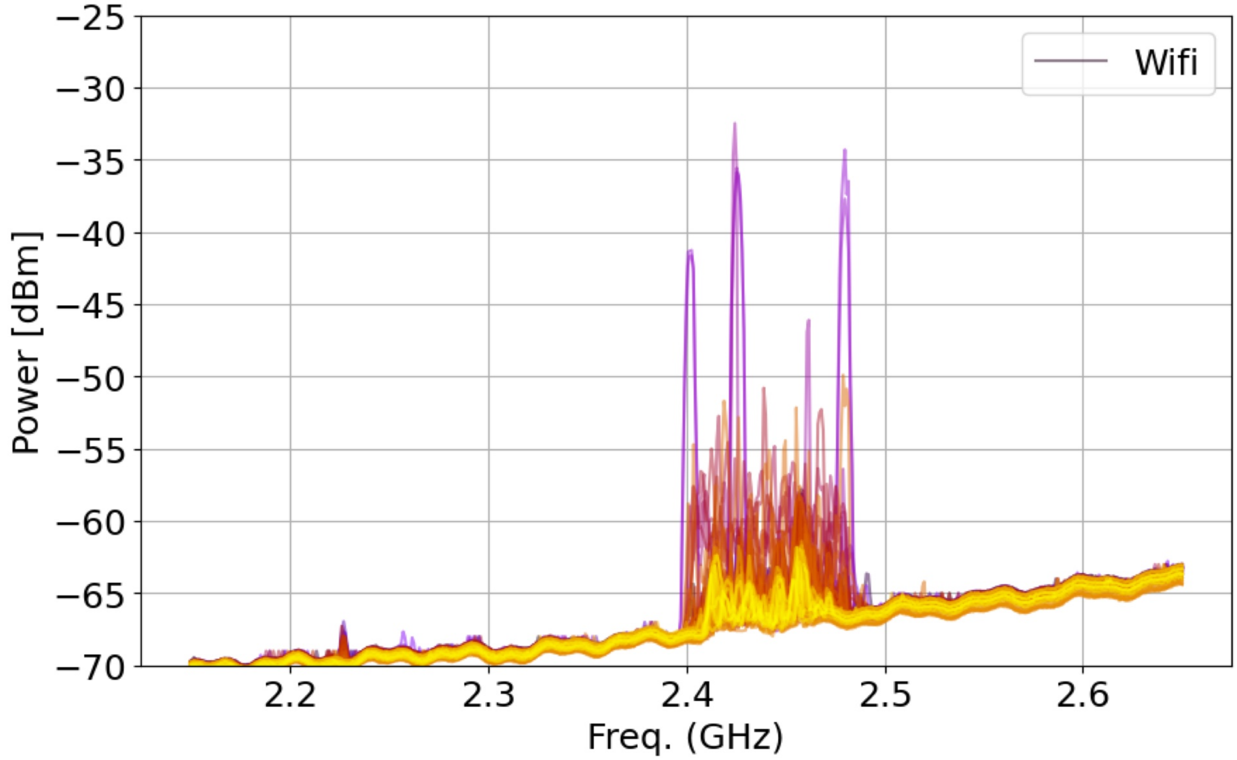
4.3 WIFI frequencies

In this section we look at local RFI in the dark sector caused by WIFI and Bluetooth enabled devices. The center frequency of the spectrum analyzer was set to 2.4 GHz and the span (bandwidth) was set to 500 MHz.



Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. The plot shows the RFI caused by a smartwatch at DSL, which was not in airplane mode. (Date: March 20, 2023)

The spectrum above shows a measurement with an active Bluetooth and WIFI enabled smartwatch on the second floor of the Dark Sector Lab building. The device was active for less than 15 minutes, hence it is only seen in one recorded trace of the plot. In addition to that one can also see other WIFI emissions at lower power levels (below -55dBm) that are present over longer time periods.

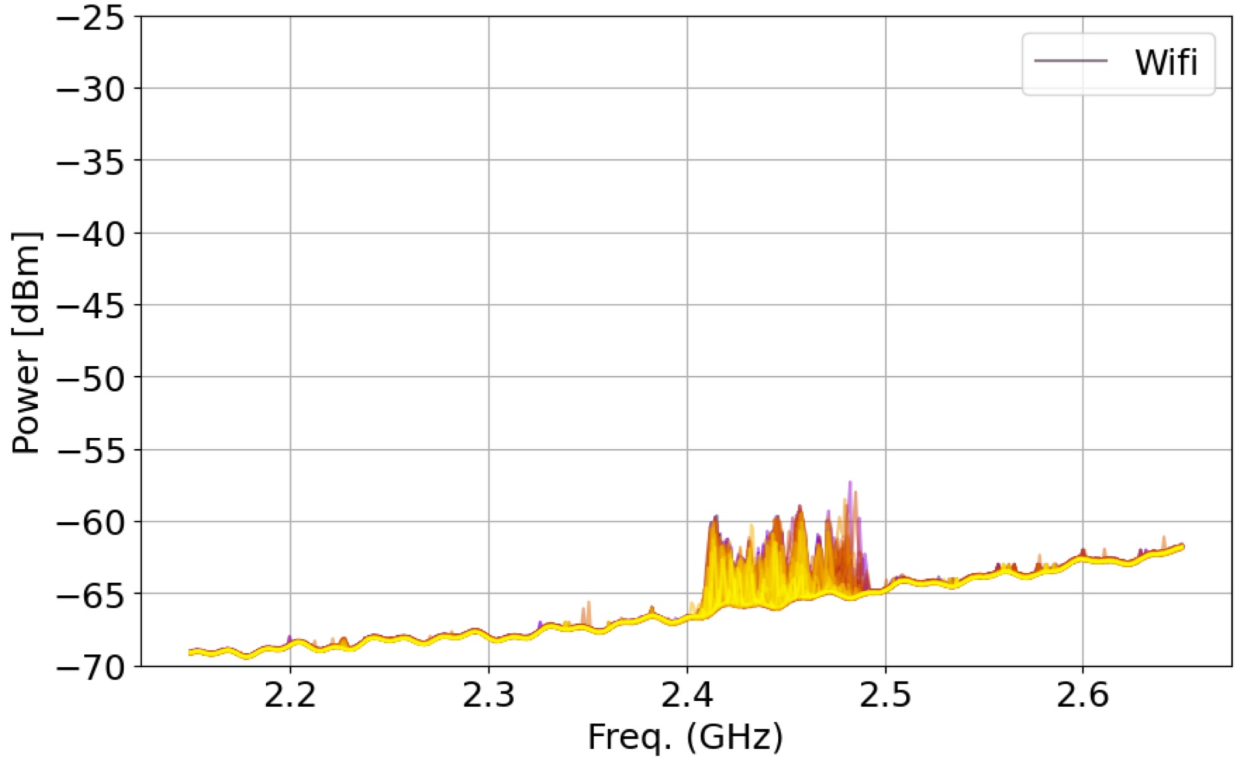


Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. The plot shows the RFI caused by a camera at DSL, which had Bluetooth enabled. (Date: March 21, 2023)

The spectrum above shows the measured spectrum of a digital photo camera which had Bluetooth enabled. The camera was located at the first floor of the Dark Sector Lab, in the receiver lab. The lower measured power level can be explained by the greater distance between the antenna and the location of the camera.

These two plots show that WIFI and Bluetooth enabled personal electronics are a significant source of RFI in the Dark Sector. Although everyone is aware to disable these devices before going into the Dark Sector, we were could to detect RFI caused by them on multiple occasions. In addition to that some smartphone manufacturers, do not disable Bluetooth when enabling Airplane mode, and users need to disable Bluetooth manually in the settings. This is something which has led to RFI on several occasions, until we could locate the source and educate personnel on these specific devices to ensure that they are really disabled.

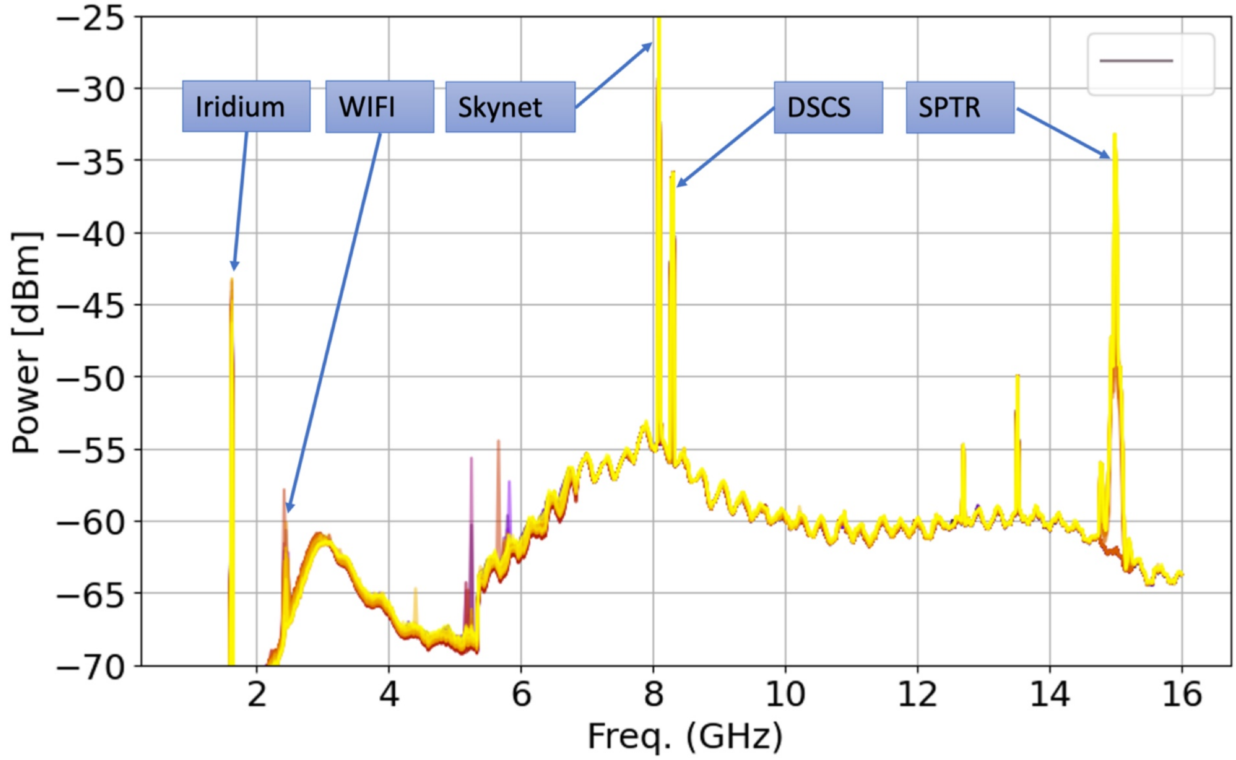
The long-term monitoring of the 2.4GHz WIFI spectrum also revealed the existence of RFI at about 5dB above the noise floor. This signal is always present and has not yet been identified. Possible sources could be the South Pole Station WIFI or some WIFI enabled devices in the RF Sector or IceCube. (See plot below.)



Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. The plot shows the unknown daily RFI in the WIFI band. (Date: March 26, 2023)

4.4 Wideband Frequency Sweep

In addition to targeted RFI measurements of known sources, we also setup a wideband frequency sweep. This sweep covered a frequency range from 1 GHz to 16GHz. The plot below shows the collected spectra for a 24 hour period. Known transmitters are labeled. However, as one can see there are a number of additional peaks visible in the spectrum. These are small in amplitude compared to the satellite internet transmissions, nevertheless it would be worth investigating their origin.



Above: all recorded spectra from a single day, with yellower colours indicating a later time of day. The plot shows a wideband frequency sweep with known sources labeled. (Date: April 12, 2023)

5 Conclusion

Based on the results of the different Starlink antenna configurations and the general RFI measurements in Section 4, we recommend locating the Starlink antenna at SPRESSO or a similar location. This will minimize any risk and impact to the science observations performed by SPT and BICEP.

Although, when comparing the RFI signal levels of the Starlink antenna with other RFI sources such as SPTR, DSCS, and Skynet we saw that the signal levels of Starlink in most configurations were lower.

The table below provides a comparison between all measured results for the various Starlink configurations as well as other detected RFI sources in the Dark Sector. The column on the right-hand side of the table normalizes the measured peak values to a power level that would appear if the measurement was performed using an omni-directional antenna. This should allow for an easier comparison between the Starlink measured values and the measurements from Section 4.

Description	Measured Peak Value	Antenna Gain	Normalized to Omni-Directional Antenna
Starlink: Configuration 2: RF Sector location without absorber. [Section 3.1.1]	≈ -40 dBm	10 dBi	≈ -50 dBm
Starlink: Configuration 2: RF Sector location with absorber. [Section 3.1.2]	≈ -47 dBm	10 dBi	≈ -57 dBm
Starlink: Configuration 3: RF Sector location with absorber and fixed mount. [Section 3.1.3]	≈ -47 dBm	10 dBi	≈ -57 dBm
Starlink: Configuration 4: SPRESSO location pointing to zenith. [Section 3.2.1]	≈ -63 dBm (Noise Floor)	10 dBi	≈ -73 dBm
Starlink: Configuration 5: SPRESSO location pointing freely. [Section 3.2.2]	≈ -58 dBm	10 dBi	≈ -68 dBm
Starlink: Configuration 6: B1 station roof location. [Section 3.3]	≈ -45 dBm	10 dBi	≈ -55 dBm
Other RFI in the Dark Sector: DSCS [Section 4.2.1]	≈ -35 dBm	0 dBi	≈ -35 dBm
Other RFI in the Dark Sector: Skynet [Section 4.2.1]	≈ -25 dBm	0 dBi	≈ -25 dBm
Other RFI in the Dark Sector: SPTR [Section 4.2.2]	≈ -33 dBm	0 dBi	≈ -33 dBm
Other RFI in the Dark Sector: WIFI [Section 4.3]	≈ -25 dBm	0 dBi	≈ -25 dBm

Table: Summary of the maximum power measured for various Starlink configurations and other RFI sources.

Finally, this report does not conclude that locating Starlink at SPRESSO or a similar location eliminates any impact on science data. We can only conclude that such a location will minimize the risk of impacts to these science projects. The final verification must come from analyzing the science data over longer time periods.