Receiving Microwave Signals from Deep-Space Probes:
Amateur DSN and the Ultimate DX

David Prutchi, Ph.D., N2QG, October 28, 2023

Figure 1 – Antennas at my QTH. I commonly use the 3.5m and 1.2 m dishes mounted on Az/El rotators for Amateur DSN

1 Abstract

Amateur reception of deep space probes is a fascinating and challenging field that blends elements of microwave RF, space communications, space exploration, and radioastronomy.

While data from space probes is commonly received and processed by space agencies using very large antennas and sophisticated equipment, it is possible for hobbyists to home-brew modest systems capable of receiving signals from deep-space probes. This is currently one of the only ways in which private citizens can directly experience planetary exploration.

This whitepaper focuses on amateur reception of deep-space probes at S- and X-band frequencies. The selection and construction of antennas, feeds, LNAs, downconverters, and receivers are discussed. Software for antenna tracking and SDR signal processing are also presented.

Lastly, examples of signals received with my home setups are shown, including transmissions from spacecraft probing Mars and Jupiter.

Note: This is an updated and greatly expanded version of my October 2020 whitepaper "Amateur DSN Lessons Learned (so far…)." The current paper was presented at the 2023 Hackaday Superconference.

2 Introduction

I've been working on my system for receiving signals from deep-space spacecraft since the summer of 2019 when KC2TDS and I built an X-band circular polarization feed and downconverter that we tested at MUD 2019.

My first true-DSN X-band DX reception happened in May 2020. I was able to receive and track Bepi-Colombo, which at that time was 15.2 million km away from Earth. The signal was received with the feed built by KC2TDS mounted on a 1.2m f/d=0.6 offset dish steered by a Yaesu G-5500 az/el rotator. I used a Kuhne LNA-8000B low-noise amplifier connected directly to the probe, and the amplified signal was sent to my first-generation N2QG downconverter (LO=8GHz) mounted on the boom. Downconverted signals (400 – 450 MHz) were received using an AOR AR-5000. The radio's IF was sampled by an SDR-14 and displayed with SpectraVue. Tracking of the probe was with PstRotator's DSN feature (Figure 2).

Later, I purchased a squeezed-tube depolarizer and super Kumar scalar ring from M0EYT (from uhf-satcom.com). KC2TDS terminated it with a waterjet-cut copper disk and added a probe which he carefully tuned with the VNA to get <20dB return loss in the 8.4 to 8.45GHz DSN band. I mounted this feed on my 3.5m dish and was able to receive Mars Express, MRO, and OSIRIS-ReX.

This whitepaper describes how I've modified my DSN system since that time, as well as the results that I've been obtaining with it using both the 1.2 and 3.5m dishes. My ODX so far is receiving the JUNO spacecraft orbiting Jupiter at a distance of 616.4 million kilometers away from Earth.

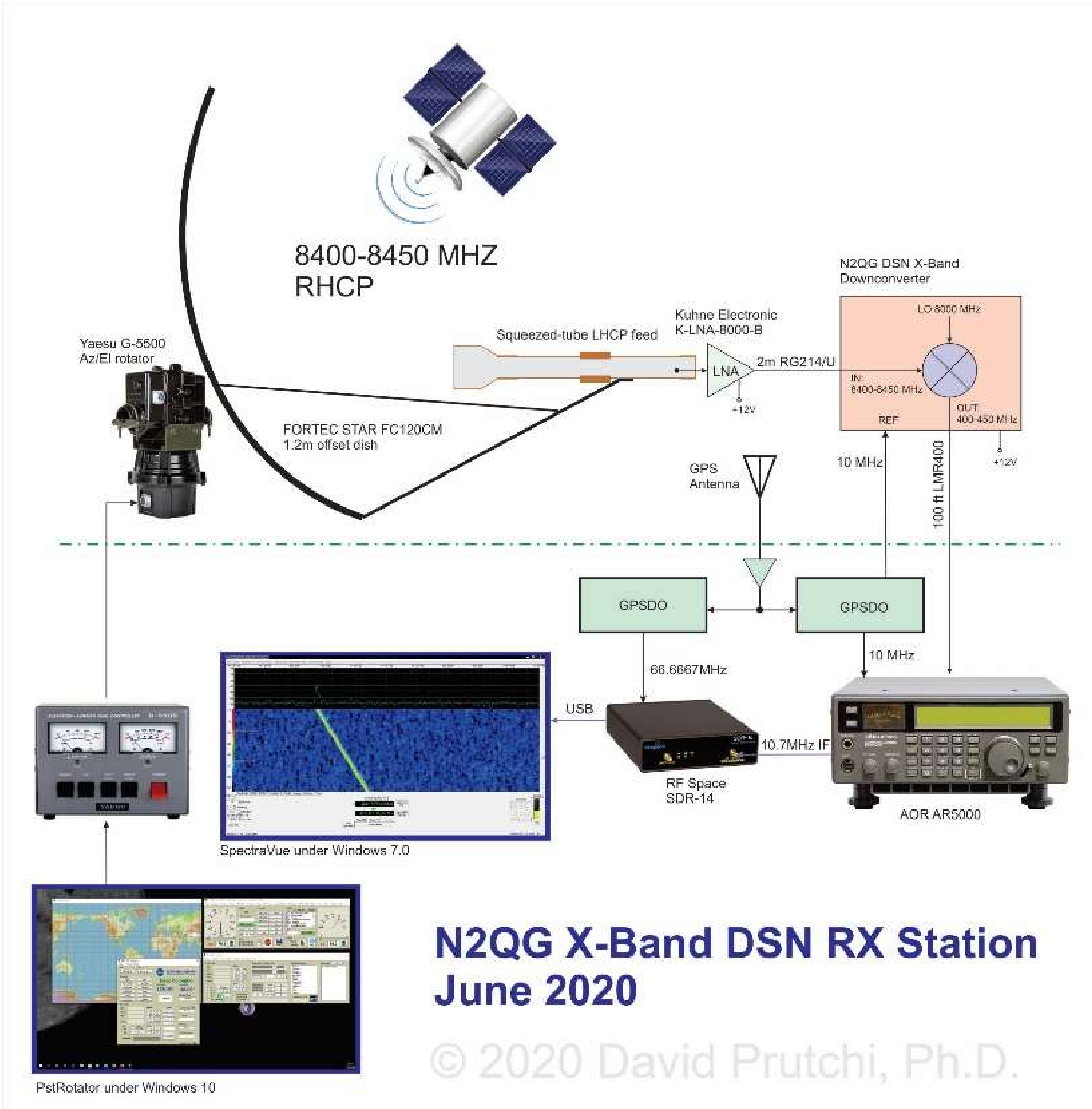


Figure 2 – Block diagram of N2QG's X-band Amateur DSN station back in June 2020.

3 The Real DSN

As shown in Figure 3, NASA's Deep-Space Network (DSN) consists of ground stations using 70m (230 feet) diameter dishes to transmit commands and receive data to/from spacecraft exploring the Solar System. The stations are 120° apart to provide coverage at all times.

Besides NASA, the European Space Agency operates its own set of deep-space stations using 35m dishes. China, Russia, and India also have their own large-dish ground stations around the globe (Figure 4).

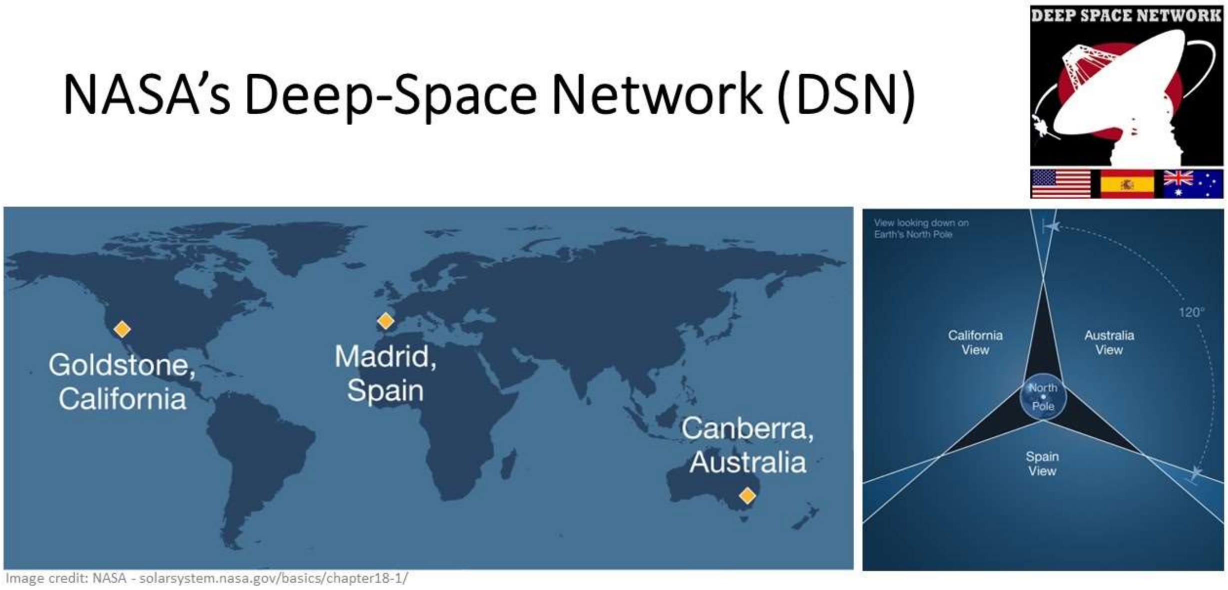


Figure 3 – NASA's Deep-Space Network (DSN) consists of ground stations using 70m (230 feet) diameter dishes to transmit commands and receive data to/from spacecraft exploring the Solar System. The stations are 120° apart to provide coverage at all times.

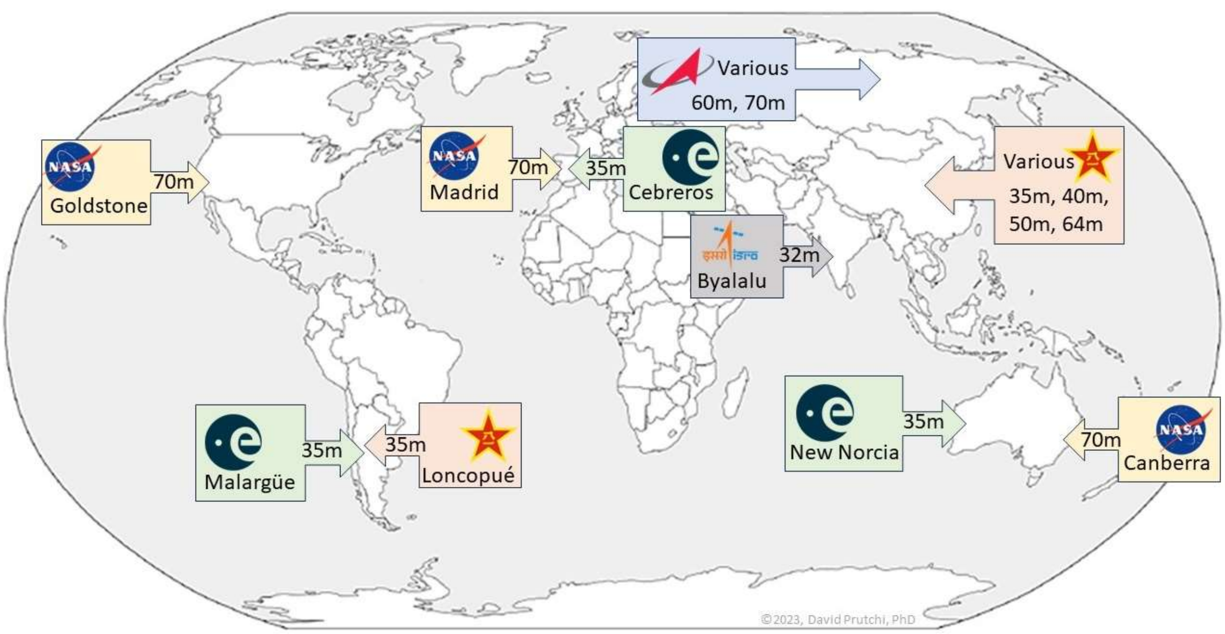


Figure 4 - Besides NASA, the European Space Agency operates its own set of deep-space stations using 35m dishes. China, Russia, and India also have their own large-dish ground stations around the globe.

4 The Amateur DSN Challenge

The need for very large antennas is because of the huge free-space path loss suffered by signals travelling millions of kilometers. In the example of Figure 5, the JUNO probe orbiting Jupiter uses a 28W transmitter and a 2.5m dish to send data to Earth. The signal travels an average of 715 million km to be received by one of NASA's 70m dishes at around -131dBm. In contrast, with my little 3.5 dish, I would barely receive -152 dBm, and that's theoretical because my dish is nowhere near ideal.

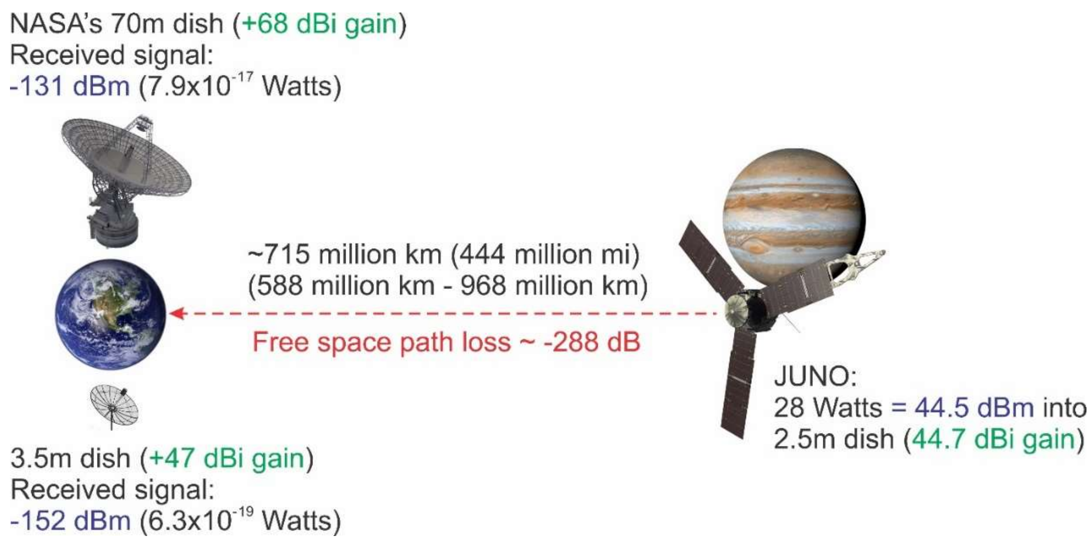


Figure 5 – Free-space path loss between deep-space spacecraft and receiving stations on Earth need to be compensated by using ground antennas with very high gain. Even with NASA's 70m dishes, the received power is -131 dBm. An ideal 3.5m amateur antenna would yield barely -152 dBm.

With such small signal on a small antenna, what Amateur DSN receivers get to see is just the residual carrier. Figure 6 shows a signal received from the Tianwen-1 probe orbiting Mars. On the left pane, the signal received by AMSAT Germany using a 20m dish shows modulation sidebands. On the right pane, the signal that I can receive using a converted 3.5 m "Big Ugly Dish" meant for C-band TVRO is just the residual carrier.

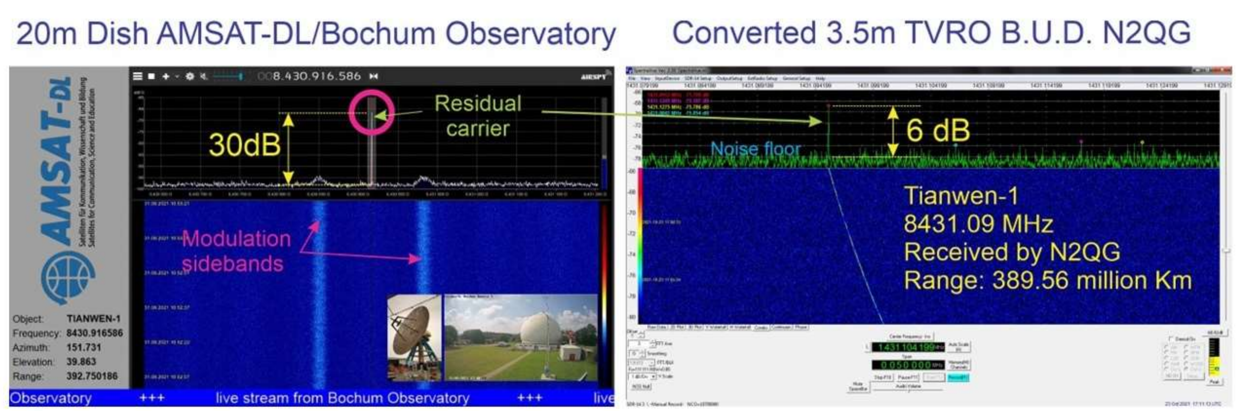


Figure 6 – Left pane: Signal received from the Tianwen-1 probe orbiting Mars by AMSAT Germany using a 20m dish. Right pane: Signal received from same spacecraft received using a converted 3.5 m "Big Ugly Dish" meant for C-band TVRO.

Locally-generated interference can generate signals at the frequencies of interest, but it is possible to confirm that the signal is actually coming from a spacecraft by looking at its Doppler shift. For example, in Figure 7 the signal from Tianwen-1 is shown along that of a nearby GPS-disciplined oscillator in my shack that is transmitting a weak local signal similar to that of the spacecraft.

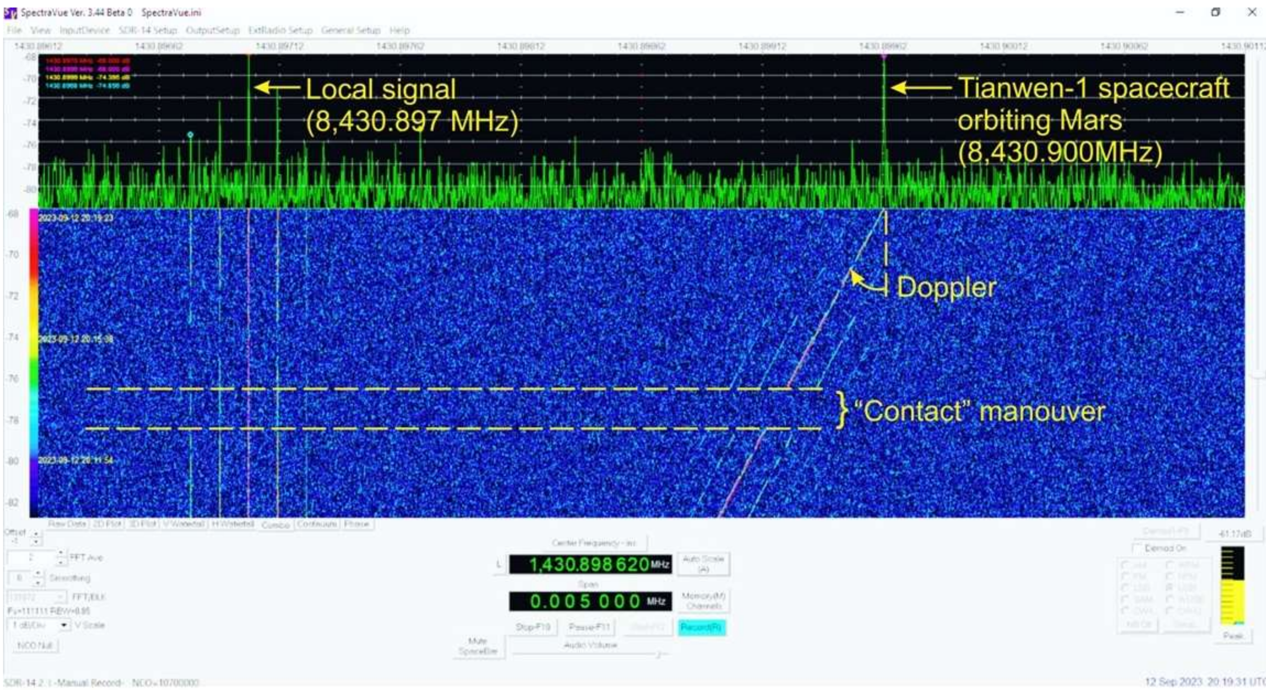
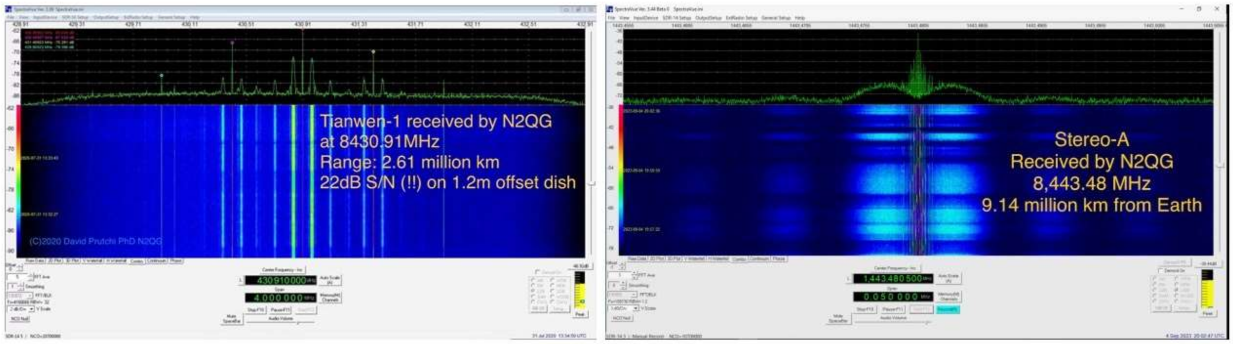


Figure 7 – Signal from Tianwen-1 spacecraft orbiting Mars along with a locally-generated GPS-locked signal. The 8,430.900 MHz signal can be confirmed to come from the spacecraft because of its Doppler shift, as well as because it disappears when the dish is moved slightly to the side.

The first clue that the signal on the right comes from a spacecraft is that it has a changing Doppler shift since it is a non-geostationary spacecraft which moves with respect to my receiver, while a local source on the left of the chart remains at the same frequency, or at least its drift doesn't match the characteristics of the Doppler shift expected for the spacecraft.

The other way to confirm that the signal is coming from a spacecraft is to move the dish slightly to the side so that it doesn't point in the direction of the target. The spacecraft's signal is expected to disappear, while a local signal would most probably remain visible. Moving back the dish should reacquire the spacecraft with the expected Doppler.

There are nevertheless cases when spacecraft are close enough to Earth that the signal picked up by a small Amateur DSN dish is strong enough to be demodulated and sometimes even decoded. For example, in Figure 8, the signals from Tianwen-1 just a few days after launch, or STEREO-A during its inferior conjunction with Earth yielded sufficiently strong signals on small dish antennas that modulation sidebands were very easy to see, enabling demodulation and decoding.



Tianwen-1 on its way to Mars, 8 days after launch (July 31, 2020)

STEREO-A close after its "inferior conjunction" (August 12, 2023 at 8.3 million km)

Figure 8 – The modulation sidebands from spacecraft can often be received with amateur DSN dishes when the probes are close to Earth, enabling demodulation and decoding.

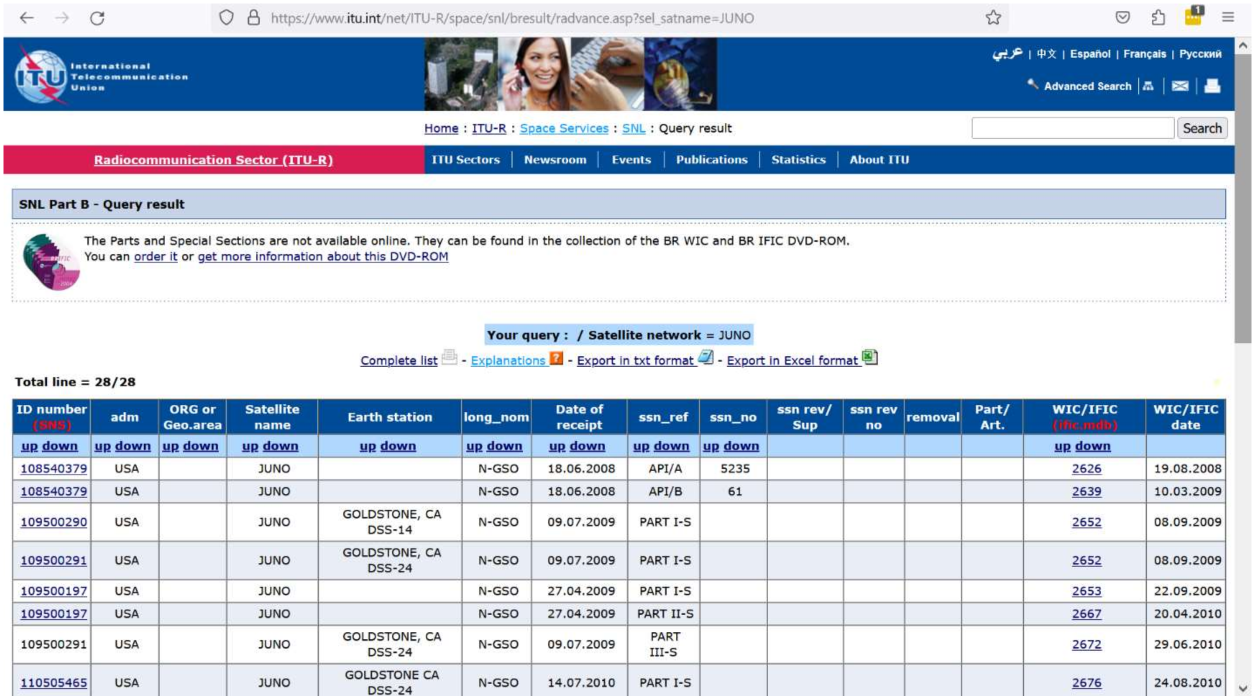
5 DSN Frequencies

The International Telecommunications Union has assigned specific bands for communicating with deep-space probes as shown in Figure 9. Details on the frequency and channel allocations are available at: https://deepspace.jpl.nasa.gov/dsndocs/810-005/201/201D.pdf Amateur stations are commonly designed to cover the 2.2-2.9 GHz S-band and 8.4-8.5 GHz X-band ranges. As discussed below in Section 14, being able to also receive the 7.25 – 7.75 GHz military satellite X-band is very useful when tuning an X-band deep-space system.

Band	Deep Space (>2,000,000 km from Earth)		Near Space (<2,000,000 km from Earth)	
	Uplink (Earth to Spacecraft)	Downlink (Spacecraft to Earth)	Uplink (Earth to Spacecraft)	Downlink (Spacecraft to Earth)
S band	2,110 – 2,120 MHz	**2,290 – 2,300 MHz**	2,025 – 2,110 MHz	**2,200 – 2,290 MHz**
X band	7,145 – 7,190 MHz	**8,400 – 8,450 MHz**	7,190 – 7,235 MHz	**8,450 – 8,500 MHz**
Military X band	-	-	7,900 – 8,400 MHz	**7,250 – 7,750 MHz**
K band	(none)	(none)	(none)	25,500–27,000
K_a band	34,200 – 34,700 MHz	31,800 – 32,300 MHz	(none)	(none)

Figure 9 – Bands assigned by the International Telecommunications Union (ITU) for communicating with deep-space probes. The military satellite X-band allocation is also shown because it is very useful for tuning X-band systems.

Spacecraft frequencies are registered with the International Telecommunications Union, but as shown in Figure 10, finding the information from records is not very straightforward, and there are nations, like China, who like to obfuscate it.


Home : ITU-R : Space Services : SNL : Query result

Radiocommunication Sector (ITU-R) | ITU Sectors | Newsroom | Events | Publications | Statistics | About ITU

SNL Part B - Query result

The Parts and Special Sections are not available online. They can be found in the collection of the BR WIC and BR IFIC DVD-ROM.
You can order it or get more information about this DVD-ROM

Your query : / Satellite network = JUNO

Complete list - Explanations - Export in txt format - Export in Excel format

Total line = 28/28

ID number (SNS)	adm	ORG or Geo.area	Satellite name	Earth station	long_nom	Date of receipt	ssn_ref	ssn_no	ssn rev/ Sup	ssn rev no	removal	Part/ Art.	WIC/IFIC (ific.mdb)	WIC/IFIC date
up down	up down	up down	up down	up down	up down	up down	up down	up down					up down	
108540379	USA		JUNO		N-GSO	18.06.2008	API/A	5235					2626	19.08.2008
108540379	USA		JUNO		N-GSO	18.06.2008	API/B	61					2639	10.03.2009
109500290	USA		JUNO	GOLDSTONE, CA DSS-14	N-GSO	09.07.2009	PART I-S						2652	08.09.2009
109500291	USA		JUNO	GOLDSTONE, CA DSS-24	N-GSO	09.07.2009	PART I-S						2652	08.09.2009
109500197	USA		JUNO		N-GSO	27.04.2009	PART I-S						2653	22.09.2009
109500197	USA		JUNO		N-GSO	27.04.2009	PART II-S						2667	20.04.2010
109500291	USA		JUNO	GOLDSTONE, CA DSS-24	N-GSO	09.07.2009	PART III-S						2672	29.06.2010
110505465	USA		JUNO	GOLDSTONE CA DSS-24	N-GSO	14.07.2010	PART I-S						2676	24.08.2010

Figure 10 – Spacecraft frequencies are registered with the International Telecommunications Union, but finding the beacon frequency from records is not very straightforward

An easier way to find these frequencies, at least for NASA/ESA spacecraft, is to look at the webpage of the Australian Communications and Media Authority which publishes the frequencies of spacecraft supported by the NASA station in Canberra and ESA station in New Norcia (Figure 11).

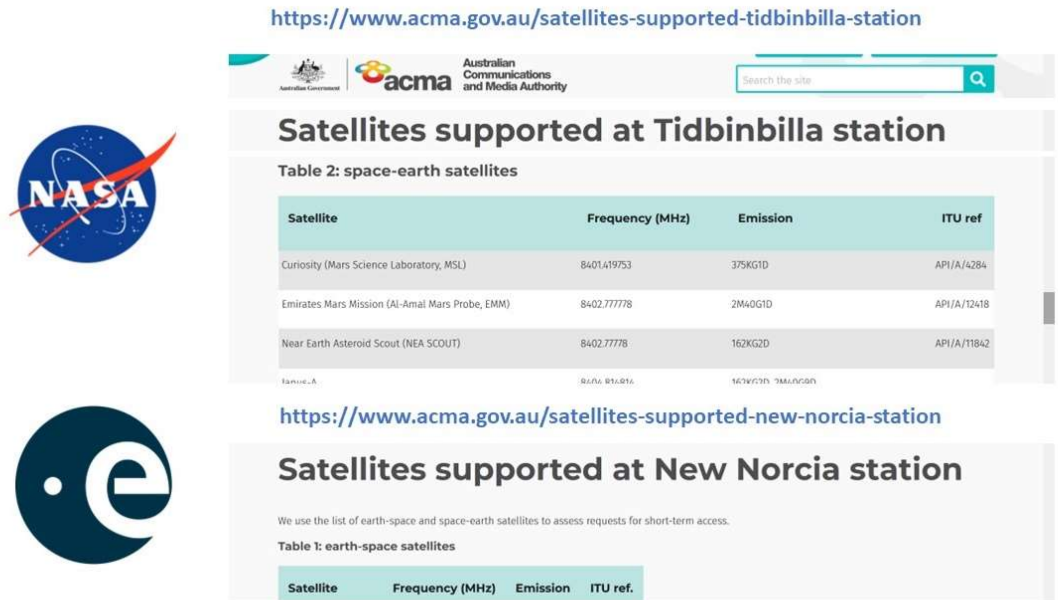


Figure 11 – the Australian Communications and Media Authority which publishes the frequencies of spacecraft supported by the NASA station in Canberra and ESA station in New Norcia

6 The Amateur DSN Station

Figure 12 shows the layout of a basic Amateur DSN setup consisting of a dish reflector that focuses onto a feed which outputs its signal into a low-noise amplifier. Wideband communications receivers and high-end SDRs are often able to receive directly in the S-band, but in the X-band a downconverter is always necessary to get the signal into a range that can be sent down a coax and received by equipment in the shack. It is essential that the downconverter and receiver will be locked to an atomic frequency reference such as a rubidium clock, or more easily a GPS-disciplined oscillator.

Importantly, the dish must be accurately pointed at the intended target which is in constant relative movement to Earth, so the Azimuth/Elevation positioner has to be computer-controlled using ephemeris data provided by NASA's JPL.

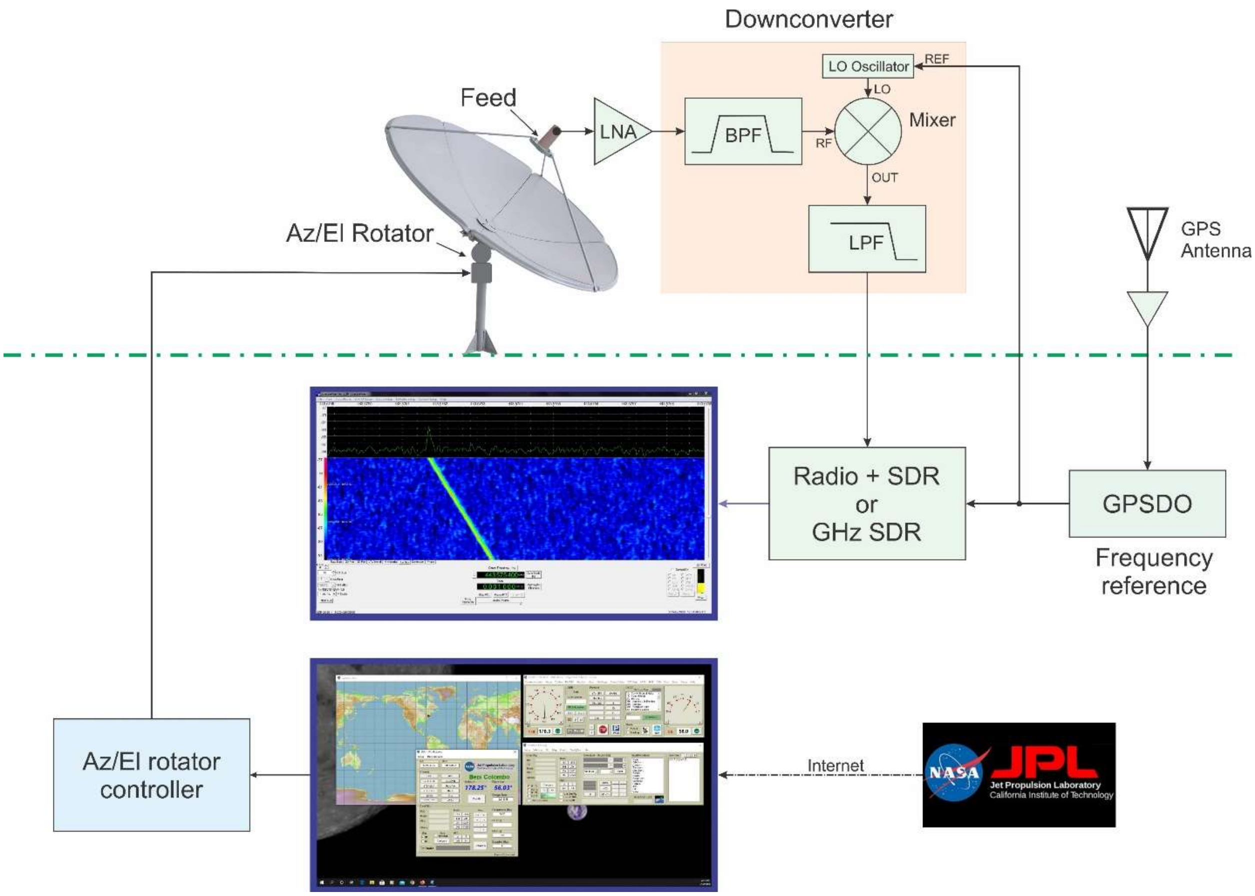


Figure 12 – Block diagram of a basic Amateur DSN station

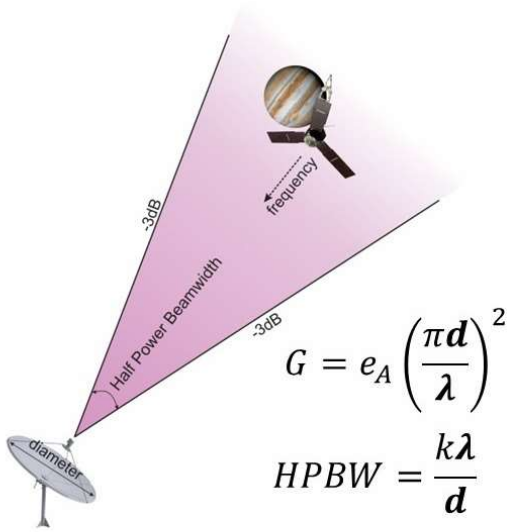
The following sections will describe each of these components in more detail.

7 Antenna (Reflector)

As shown in Figure 13, Amateur DSN dishes typically range between 0.6m, like Scott Tilley's "Mighty Little Dish" to 3.5m like mine. Amateurs also sometimes have access to larger dishes, like the ones 6.1m in diameter of the Allen Telescope Array, or a 20m dish operated jointly by AMSAT Germany and the Bochum observatory. In contrast, the big boys at NASA, ESA, and other space agencies use dishes that are commonly 35 or 70 m in diameter.

Figure 13 - Amateur dishes typically range between 0.6m, like Scott Tilley's "Mighty Little Dish" to 3.5m like mine. Amateurs also sometimes have access to larger dishes, like the ones 6.1m in diameter of the Allen Telescope Array, or a 20m dish operated jointly by AMSAT Germany and the Bochum observatory. In contrast, NASA and ESA use dishes that are 35 or 70 m in diameter.

The larger the dish the higher its gain, but larger is not always better because the larger the dish the more difficult it is to move and point accurately. As shown in Figure 14, a 0.6 m dish has a half-power beamwidth of 3.6°, so it can be pointed even by hand. A relatively large amateur dish like my 3.5 m needs to be pointed so that the target spacecraft will be within a half degree angle. NASA needs to point its gigantic dishes with milli-degree precision. -3dB is half the signal, so much better than this is actually required for detecting spacecraft in deep space.



$$G = e_A\left(\frac{\pi \boldsymbol{d}}{\boldsymbol{\lambda}}\right)^2$$

$$HPBW = \frac{k\boldsymbol{\lambda}}{\boldsymbol{d}}$$

Diameter [m]	@ 8.4 GHz	
	Max Theoretical Gain [dB]	Ideal HPBW [degrees]
0.6	32.3	3.57
1.2	38.3	1.79
2.4	44.3	0.89
3.5	47.6	0.61
6	52.3	0.36
70	73.6	0.03

Figure 14 – Larger dishes have higher gain, but require more accurate pointing. The best choice in dish size is the largest antenna that one can point with the required accuracy.

So, the larger the antenna, the more pointing precision is required, which at the same time is more difficult when the object to be moved precisely is large and heavy. Bottom line – the best choice is the largest dish that one can point with the required accuracy.

I commonly use two dishes for Amateur DSN (Figure 1). One is an offset dish 1.2 m in diameter, and the other is a 3.5 m prime-focus dish.

7.1 1.2m, f/d=0.6 offset dish (FORTEC STAR FC120CM)

My smaller dish is shown in Figure 15. It is a Fortec Star 120 offset dish designed for Free-to-Air (FTA) satellite reception. It's a very nice dish that I've had since 2006 and have used in the 23/13cm ham bands, as well as for 21cm (hydrogen-line) radio-astronomy. Table 1 shows the manufacturer's specs.

I like this dish very much for a number of reasons. First of all, it is relatively light, so it can be moved by a light-weight rotator like the Yaesu G-5500. Second, the focal point is well defined (since it is made for Ku Band satellite FTA TV), and it's easy to reach due to it being an offset design. Lastly, it has an estimated gain at 8.45 GHz of around 38.6 dBi, which results in a full-beam width of around 2°, which is very forgiving regarding pointing accuracy. By the way, the estimated gain in the S-band is 27.7 dBi. As shown in Table 2, signal levels are quite good for what I would expect from a small dish like this.

Figure 15 – Fortec Star 1.2m, f/d=0.6 offset dish shown with S-, X-, and Ku-band feeds

Table 1 – Manufacturer's specifications of the FORTEC STAR FC120CM offset dish

Specification	Value
REFLECTOR	
Type	Offset
Offset Angle	24.62^{0}
Diameter	120 cm x 132 cm
Aperture Efficiency	75% min.
C – Band Gain @ 4.0 GHz	32.78 dB
KU – Band Gain @12.5 GHz	43.32 dB
F/D Ratio	0.6
Focus Length	720 mm
Material	Galvanized Steel
Finish	Polyester Powder Coating
Color	Grey / Cool Grey
MOUNTING	
Mounting Type	Ground, Pole & Wall Mount
Adjustment Type	AZ / EL Mount
Elevation Angle Range	25° - 77°; 17° - 90°
Azimuth	0° - 360°
Material	Steel
Finish	Polyester Powder Coating
Color	Grey / Cool Grey
Pole Diameter Acceptable	45 – 75 mm
Net Weight	17.0 kg
ENVIRONMENT	
Operational Winds	25 m / sec
Survival Winds	50 m / sec
Ambient Temperature	-40°C ~ +60°C
Relative Humidity	0 ~ 100 %

Table 2 – Some of the spacecraft received by N2QG using the 1.2m, f/d=0.6 offset dish

Spacecraft	Date	Range (millions of km)	RX Frequency (MHz)	SNR (dB)	Comments
S-Band					
James Webb Space Telescope	December 31, 2021	0.63	2270.4966	10	Locked with Madrid -119.1 dBm
Global Geospace Science (GGS) WIND	November 15, 2020	1.48	2274.9252	12	Locked to Goldstone -127.46 dBm
Chandra X-ray Observatory	November 15, 2020	0.12	2249.9961	26	Locked to Madrid -105.04 dBm
QueQiao Lunar Relay Satellite	November 15, 2020	1.62	2230.7980	12	
Solar and Heliospheric Observatory (SOHO)	November 15, 2020	1.62	2245.0086	16	Locked to Goldstone -109.84 dBm
X-Band					
OSIRIS-ReX	September 13, 2020	312.82	8445.5236	4	Locked to Goldstone -120.75 dBm
OSIRIS-ReX	October 10, 2020	328.59	8445.7429	4	Locked to Goldstone -121.24 dBm. Received signal shown in Figure 16
STEREO-A	July 25, 2020	180	8443.5975	10	downconverter v. 19Jul2020 with 20dB att in shack
Tianwen-1	July 31, 2020	2.61	8430.91	22	
Mars 2020 Perseverance	July 31, 2020	0.39	8414.8736	24	
Hope Emirates Mars Mission	July 22, 2020	0.89	8402.6693	10	LHCP
Mars Reconnaissance Orbiter (MRO)	October 15, 2020	62.91	8439.3067	16	Mars in opposition. Prior lock to Madrid showed signal -99 dBm

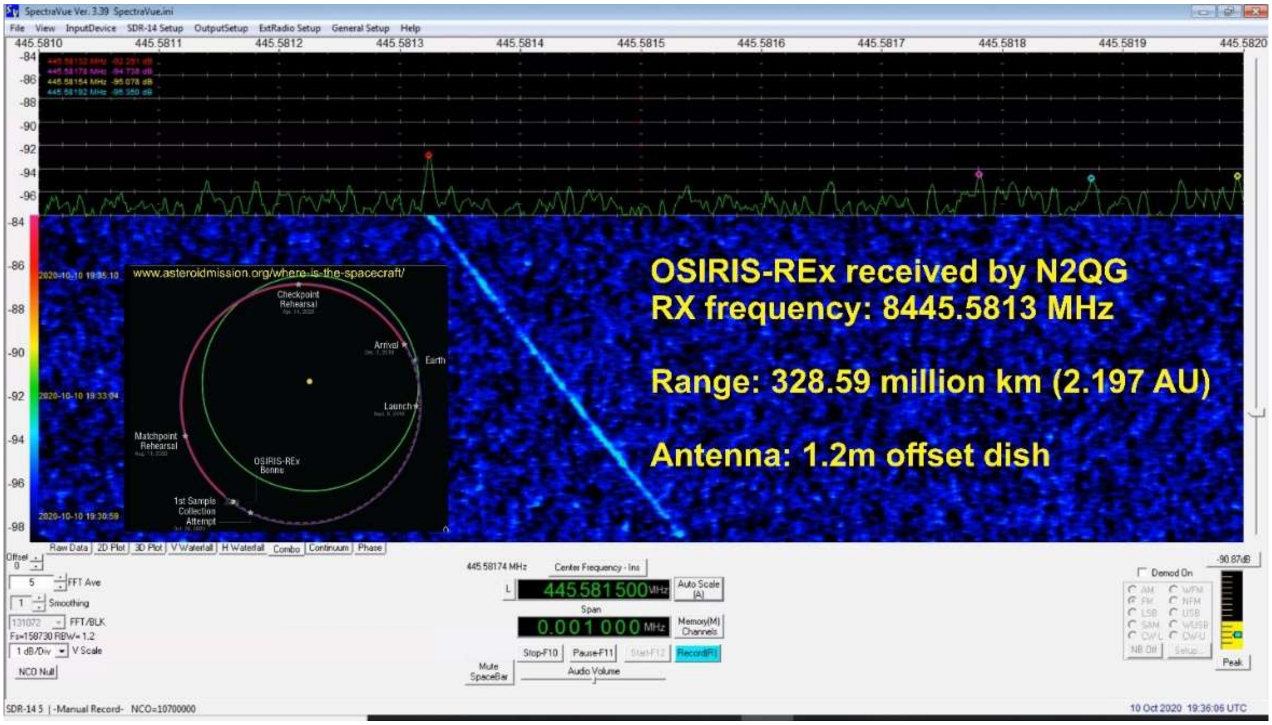


Figure 16 - OSIRIS-ReX received by N2QG at 8445.742935 MHz using 1.2m offset dish. Spacecraft was locked to NASA's Goldstone DSN, which reported a received power of -121.24 dBm. This is my ODX with the 1.2m dish.

My original intention in setting up this dish was to use it as a testbed to figure out how to track DSN spacecraft, which was coincidentally obviated by the introduction of the DSN feature in PstRotator at the time I started working on Amateur DSN. It's still a great platform for observing S-band satellites and lunar probes. However, 1.2m is much too small to receive some of the planetary probes. Nevertheless, I still use it to test feeds and tweaks to my X-band downconverter before moving them to the 3.5 m dish.

7.2 3.5m (12ft) C/Ku-Band Prime Focus Mesh Satellite Dish (Tek2000.com)

I purchased my 3.5m dish from Tek2000.com, who sell it as a consumer-grade high-performance TVRO C/Ku antenna. I converted it for Az/El positioning with a SPID BIG-RAS Rotator. KC2TDS designed and built new steel feed arms with waterjet-cut supports and a very flexible feed bracket that allows for quick exchange of feedhorns.

Table 4 shows some of the spacecraft received using this dish, including the challenging MRO and Mars Express (when Mars is not in opposition) with quite good signals (Figure 18 and Figure 19). It is with this dish that I received JUNO orbiting Jupiter at a range of 670 million km.

Figure 17 – 3.5m mesh dish with X-band feed and N2QG downconverter mounted on the feed-point bracket.

Table 3 - Manufacturer's specifications of the consumer-grade 3.5m C/Ku-band prime focus mesh dish sold by Tek2000.com

Antenna Construction	
Material	Aluminum Mesh
Hole size	0.06" (1.5mm)
Panels	8
Rib size	1" (2.54cm) sq.
Feed Support Rods	4
Strut Length	63.5" (161.3cm)
Strut Mount	23" (58.4cm) from rim on panel face
Aperture Diameter (inner)	139" (353.1cm)
Focal Length	52.5" (129.5cm)
F/D Ratio	0.375
Finish	Polyester Powder Coating
Color	Black / Glossy Black
Weight	175 lbs
Performance	
C-Band Gain(@4.2GHz)	42.8dBi (Typ)
Ku_band Gain(@12.2GHz)	51.1dBi (Typ)
C-Band Mainlobe Beamwidth	1.5°
Ku-Band Mainlobe Beamwidth	0.40°
Mounting	
Mounting Type	Polar Mount
Polar Frame Size	40" (101.6cm) diameter
Elevation Angle Range	0° to 90°
Azimuth Range	0° to 360°
Declination Adjustment	0° to 10°
Recommended Pole Dimension	4"~4.5" (102mm~115mm)
Environment	
Operational Winds	90km/h
Survival Winds	150km/h
Ambient Temperature	-50°C to +60°C
Relative Humidity	0~100%

Table 4 – Some of the spacecraft received by N2QG using the Tek2000.com 3.5m dish

Spacecraft	Date	Range (millions of km)	RX Frequency (MHz)	SNR (dB)	Comments
OSIRIS-Rex	June 21, 2020	249.88	8445.5386	8	
	Sept 11, 2021	321.95	8445.5740	10	Locked to Goldstone - 115.79 dBm
Mars Reconnaissance Orbiter (MRO)	June 21, 2020	131.11	8439.6638	8	Locked to Goldstone. Received signal shown in Figure 18
STEREO-A	July 4, 2020	182.05	8443.57828	12	

Spacecraft	Date	Range (millions of km)	RX Frequency (MHz)	SNR (dB)	Comments
	April 15, 2023	27.83	8443.5600	38	Communicating with Madrid
	September 4, 2023	9	8443.4800	45	During inferior conjunction
Mars Express	June 12, 2020	137.66	8420.6963	6	Received signal shown in Figure 19
Anik G1	April 15, 2023	Geostationary	7297.5	10	Canadian geostationary satellite
Double Asteroid Redirection Test (DART)	November 25, 2021	0.41	8421.7009	21	Locked to Madrid -107.03 dBm
LUCY	October 24, 2021	3.61	8445.6177	20	
Wideband Global SATCOM 6 (WGS-6) MilSat	April 15, 2023	Geostationary	7602.048	30	Geostationary MilSat LHCP
Tianwen-1	September 11, 2021	394	8430.5998	8	Orbiting Mars
	April 15, 2023	239	8430.6540	12	
Perseverance (Mars 2020)	November 6, 2020	52.35	8414.6705	4	Locked to Goldstone -132.11 dBm
Emirates Mars Mission	January 18, 2021	154.92	8402.2573	8	Using dual-feed LHCP
Bepi-Colombo	December 4, 2020	203.75	8420.3790	14	
JUNO	October 18, 2021	670.03	8403.2642	3.5	My ODX so far. Locked to Goldstone -132.04 dBm

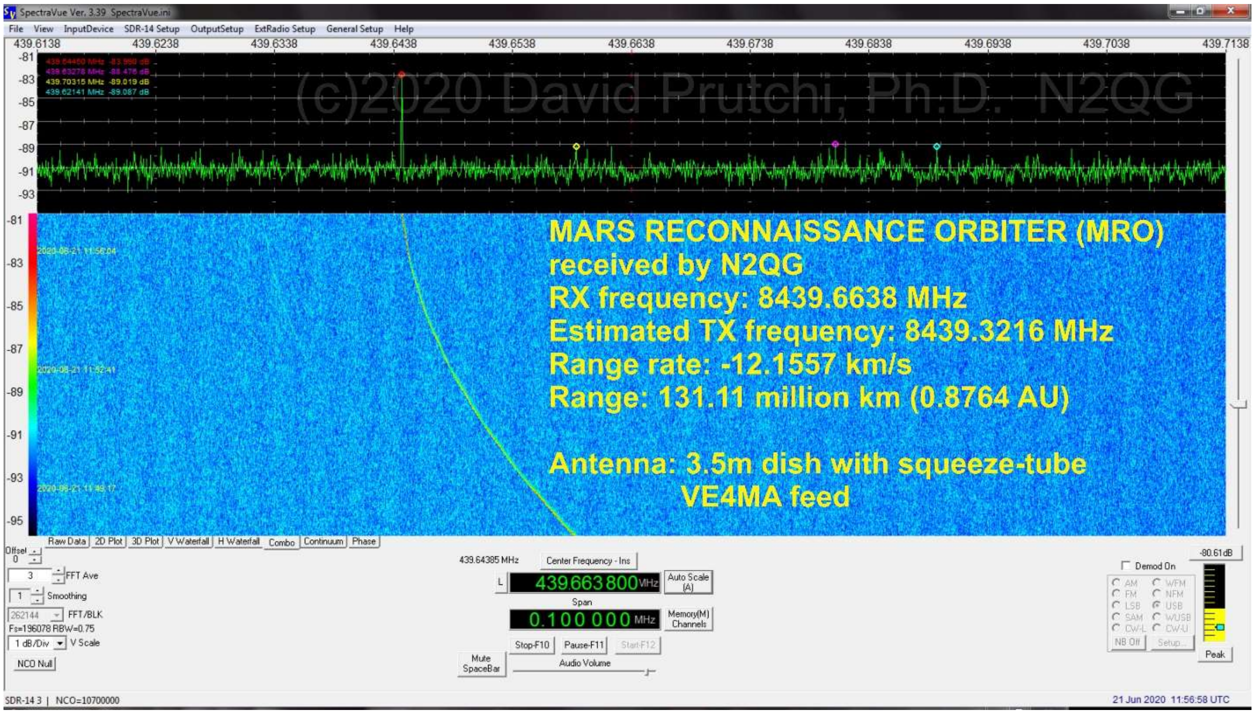


Figure 18 – MRO received by N2QG at 8439.66 MHz using 3.5m dish

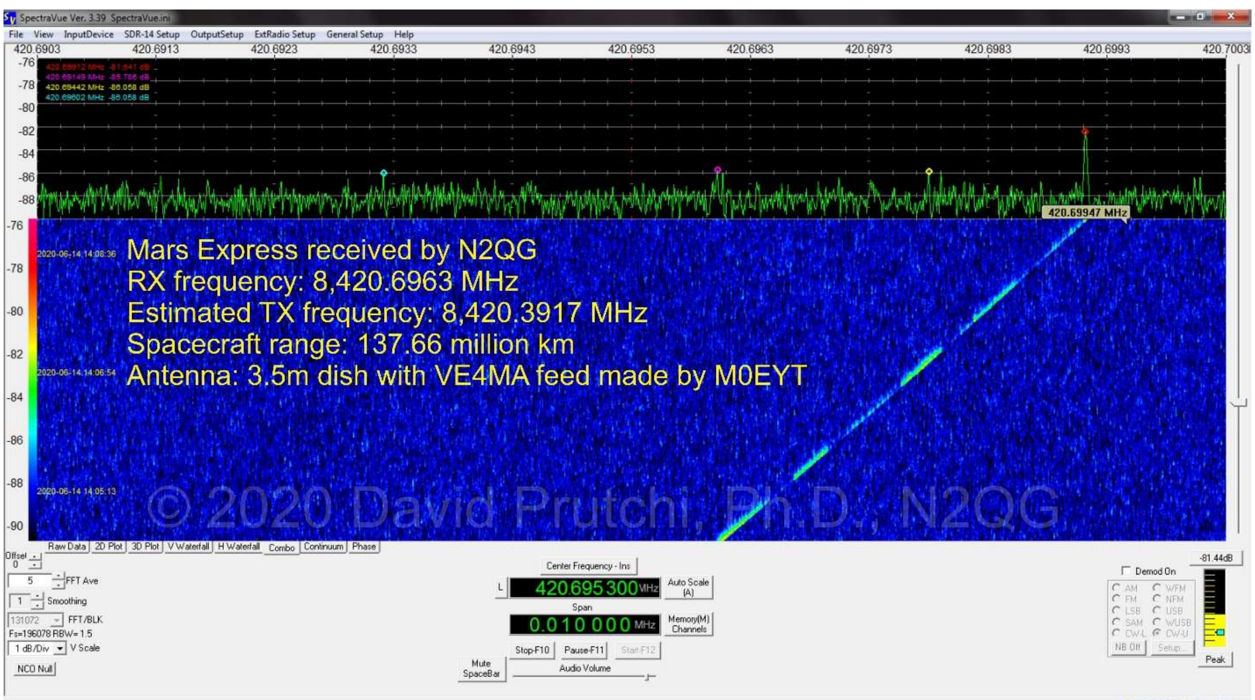


Figure 19 - Mars Express received by N2QG at 8420.6963 MHz using 3.5m dish

This dish performs superbly at 1296 MHz, and I've used it to make many challenging EME contacts, including SSTV! In spite of this, signal strengths from X-band DSN spacecraft are weaker than those expected from a dish of this size. For example, on the same day, and DSN lock, I can receive Bepi-Colombo on the 1.2m dish with around 12 dB SNR compared to 16dB on the 3.5m dish. However, M0EYT receives it at around 30 dB on his 2.4m prime dish and essentially the same feed.

Figure 20 – Evaluating surface accuracy with small mirrors attached to the reflector shows spread at the focal point.

To help diagnose, I attached many small mirrors to the reflector's surface. As shown in Figure 20, pointing at the Sun demonstrated a dispersion at the focal point, which is why I suspect that lack of surface accuracy causes a strong degradation of g/t at 8.45 GHz. At the same time, the surface is sufficiently accurate at 1296 MHz, explaining the excellent EME performance at 23 cm.

7.3 Antenna Reflector – Lessons Learned

The antenna reflector is obviously the most complex part of the system because of its size and difficulty in steering as its weight and wind load grow with size. At the same time, size alone is not the only factor driving performance, but density and surface accuracy may be even more important.

My current feeling is that I'll retire the 1.2m dish, and substitute it by a high-quality 2.4 m or 3 m TX-rated dish on a SubLunar Az/El Rotator. The specific antennas that I'm thinking about were made by Prodelin (now the Satcom & Antenna Technologies Division of CPI). These VSAT antennas are made with a tight mesh embedded in glass-fiber-reinforced polyester SMC, giving them excellent surface stability and accuracy. Alternatively, I'll look into solid 1-piece or 2-piece aluminum dishes

8 Az/El Rotator and Controller

As discussed above, accurate pointing of the antenna is essential for receiving signals from deep-space probes. The type of rotator used depends heavily on the size, weight, and pointing precision that is required.

Figure 21 – Some Az/El rotators used by amateurs to position their antennas. Left-to-right: iOptron AZ Mount Pro telescope mount used be VE7TIL to steer his 60 cm "Mighty Little Dish" together with a video camera, Yaesu G-5500 that I use to move my 1.2m dish, SPID Big RAS with my 3.5m dish, slewing 2-axis rotator used by W2HRO to position his EME dish, and Pelco 1250P heavy-duty pan/tilt CCTV camera mount used by VE7TIL for his 2m dish.

The iOptron AZ Mount Pro telescope Az/El mount is great for moving small dishes, like Scott Tilley's (VE7TIL) 60cm "Mighty Little Dish" (MLD). Dishes in the 1 – 1.2 m diameter range can be pointed with a light-duty rotator like the Yaesu G-5500. Larger dishes require heavy-duty rotators like the SPID BIG-RAS. Lately, slewing 2-axis rotators made in China meant to steer large solar cell arrays have been adapted by amateurs to move large dishes. Likewise, heavy-duty pan-tilt CCTV camera mounts have been converted into dish rotators.

I use a Yaesu G-5500 to steer the 1.2m offset dish, and a SPID BIG-RAS for the 3.5m dish.

8.1 Yaesu G-5500

The Yaesu rotator is a very basic unit, and with a 1.2m dish (1.13m^2 surface area), I'm a bit over the limit of its wind load capacity (1m^2). I placed the dish to be protected by a fig tree and the yard fence, so I haven't experienced any issues with the gears. I control the G-5500 with the stock controller, which is just a bang-bang unit with potentiometer feedback. Even with the relatively broad angle of the 1.2m dish, continuous tracking causes hiccups in the signal because of the imprecise nature of its position sensors and controller.

8.2 SPID BIG-RAS

The SPID BIG-RAS is a heavy-duty rotator that I use to steer the 3.5m dish. I have the standard-resolution model, and was originally controlling it with the SPID Rot2-Prog (RAS-1C) controller. The rotator itself has performed quite well, although its manufacture is very rough. However, the SPID controller is absolutely horrible! Not only is the controller bang-bang, which causes a huge amount of overshoot and oscillation when moving an antenna with a large moment of inertia, but its counter quickly loses calibration, so the main complaint that hams have with this rotator is the need for very frequent recalibration (often in the middle of a tracking session).

I thus bought a Green Heron RT21 AzEl, and I'm very happy with it. This unit controls the speed of rotation, so it ramps-up and ramps-down the rotator's speed for smooth tracking. In addition, Jeff - the owner of Green Heron - added an input for my US Digital T7 RS232 absolute inclinometer, which gives me absolute precision in the more problematic axis.

8.3 Rotator – Lessons Learned

High resolution and smooth tracking are critical for X-band DSN, so for my next antenna project I intend to invest in a better rotator/controller. My eye is on a Sub-Lunar Az/El rotator with a matching Green Heron RT21 AzEl. This is a very heavy-duty slewing rotator, that according to Jeff at Green Heron, can easily move a 3 m dish with 0.1° resolution and maintain better than 0.2° tracking accuracy.

Specs on the Sub-Lunar rotator are:

- Dual Axis Drives – 453 ft-lb torque
- Holding Torque – 1475 ft-lb
- Vertical Load – 6750 lb
- Resolution – 0.1°
- Positioner weight – 58 lb

9 Feed

The purpose of the feed is to convert the free space electromagnetic signal collected by the dish into an electric current that can be amplified and processed.

Deep-space probes transmit circularly-polarized signals, so the feed must be built to receive a circularly-polarized wave of the opposite polarity as the signal sent by the spacecraft. This is because when the feed is mounted on a parabolic antenna, the spacecraft signal's polarization mirror-images the original after being reflected by the dish.

Popular ways of receiving circularly-polarized signals are to use helical feeds, or to turn them into linearly-polarized waves through a "depolarizer" such that they can be efficiently detected through a small wire probe. Alternatively, orthogonal linear probes can be combined with the appropriate delay to receive circularly-polarized signals.

9.1 S-Band Feed

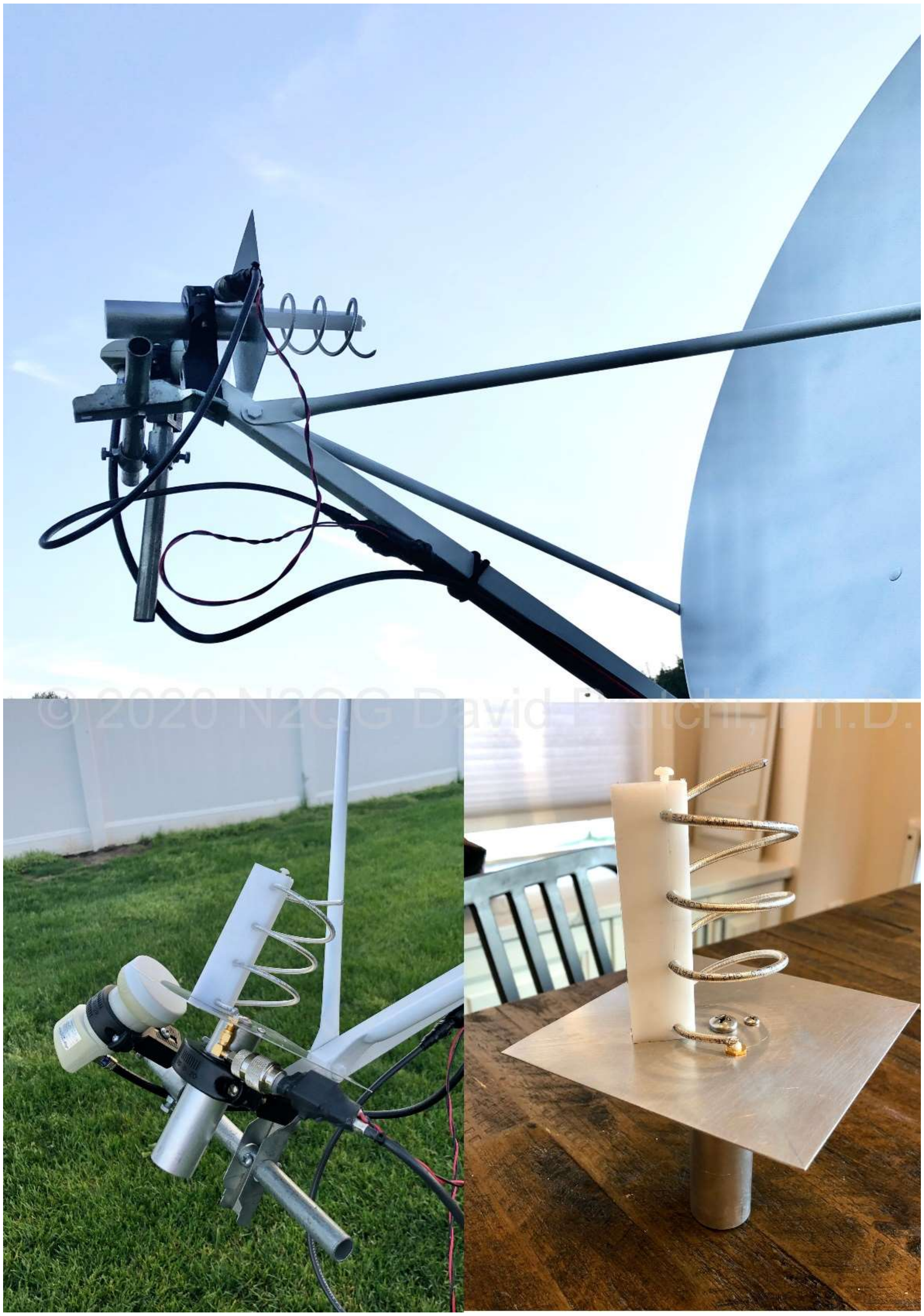


Figure 22 – My S-band feed for the 1.2m offset dish is a home-built 3.5-turn helical antenna

My S-band feed for the 1.2m offset dish is the 3.5-turn helical antenna shown in Figure 22. VSWR is quite OK (1.5:1 to 1.6:1) within the Near-Earth and Deep-Space S-band (2.2 to 2.3 GHz) as shown in Figure 23.

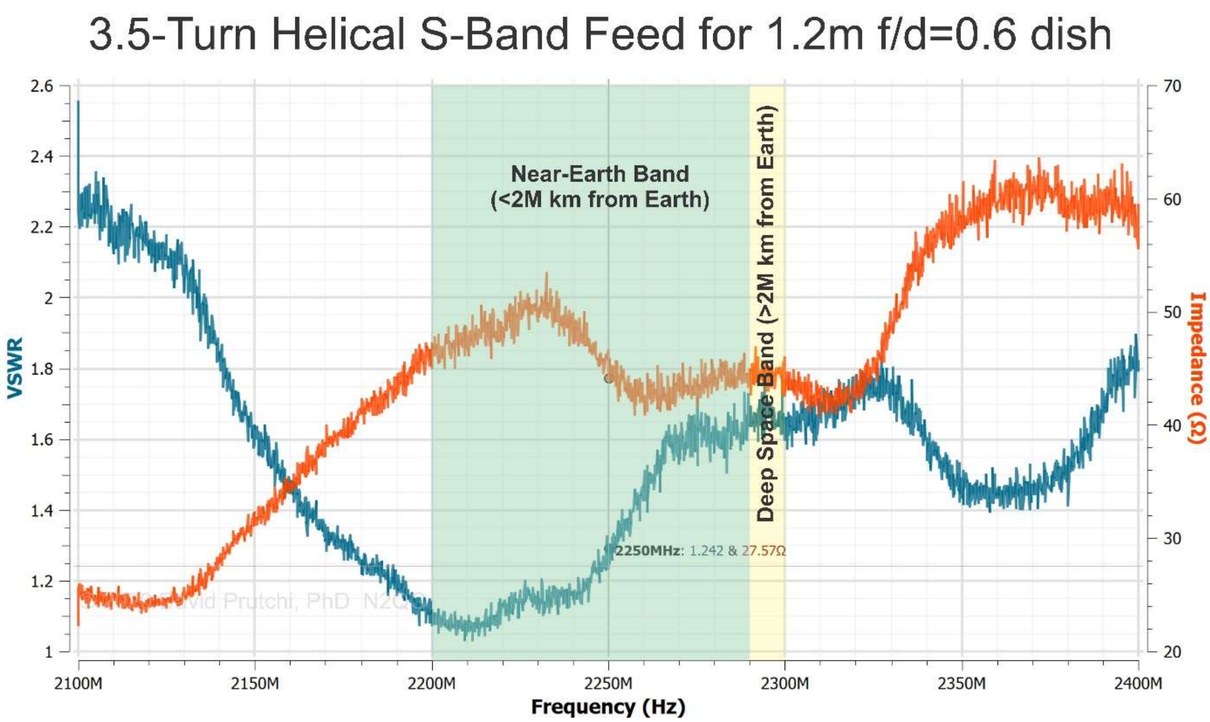


Figure 23 – VSWR of my 3.5-turn helical S-band feed for 1.2 m dish

9.2 X-Band Feed

Amateur x-band feeds are commonly built from copper plumbing hardware. I've used two feeds so far. Both are made of copper pipe and have squeezed-tube circular depolarizers. The first was built by KC2TDS based on the dimensions of the feedhorn constructed by SQ5KTM (Figure 24).

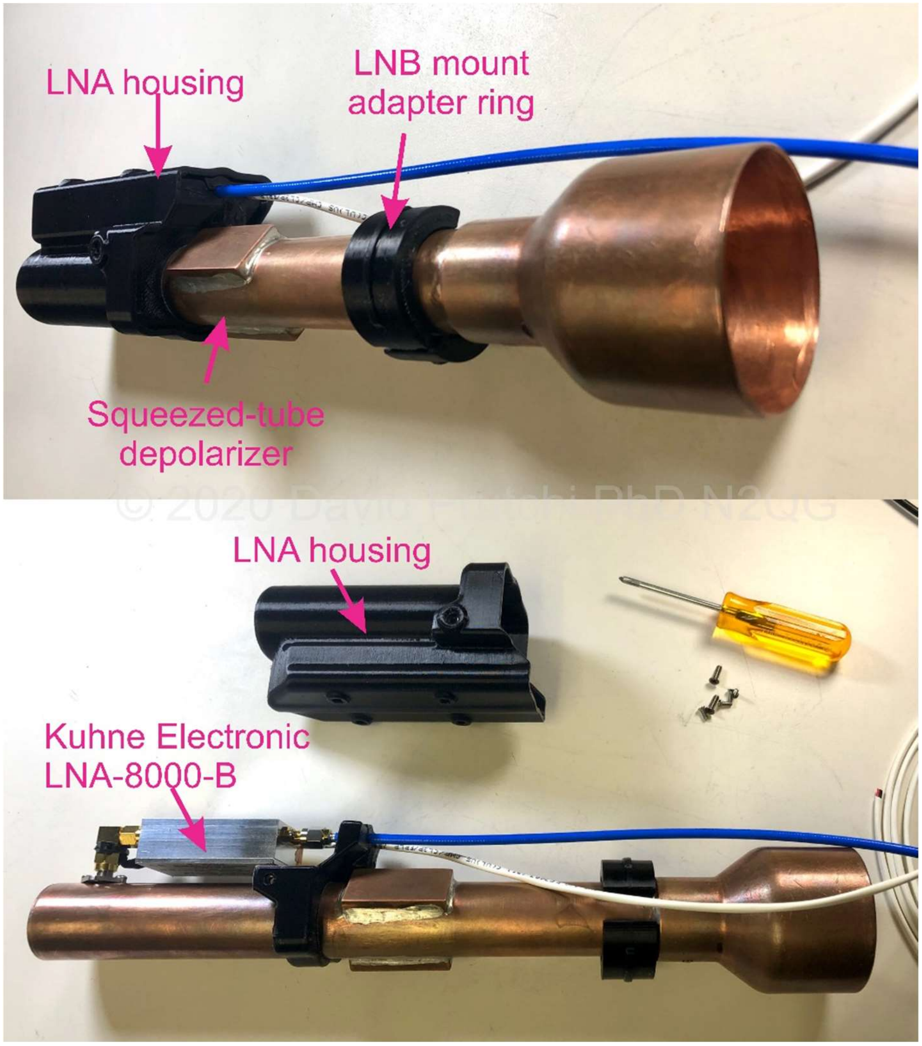


Figure 24 – 8.45GHz squeezed-tube feed built by KC2TDS based on SQ5KTM's feed

The problem with this feedhorn is that it has a fixed beamwidth, so it matches a single f/d. It underperformed in both the 1.2m dish (f/d=0.6) and the 3.5m dish (f/d=0.37).

Taking advantage that M0EYT was building a batch of squeezed-tube depolarizers, I purchased one with a matching "Super Kumar" VE4MA scalar ring (Figure 25, from uhf-satcom.com). KC2TDS terminated it with a waterjet-cut copper disk and added a probe which he carefully tuned with the VNA to get <20dB return loss in the 8.4 to 8.45 GHz DSN band.

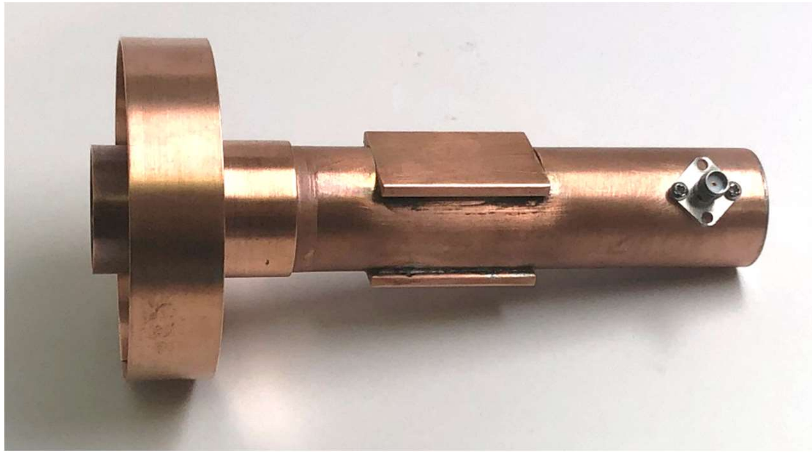


Figure 25 - Squeezed-tube depolarizer and VE4MA "Super Kumar" scalar ring built by M0EYT

The probe, as shown in Figure 26, is made from a long-stem SMA connector with most of the insulation removed and cut to ¼ λ

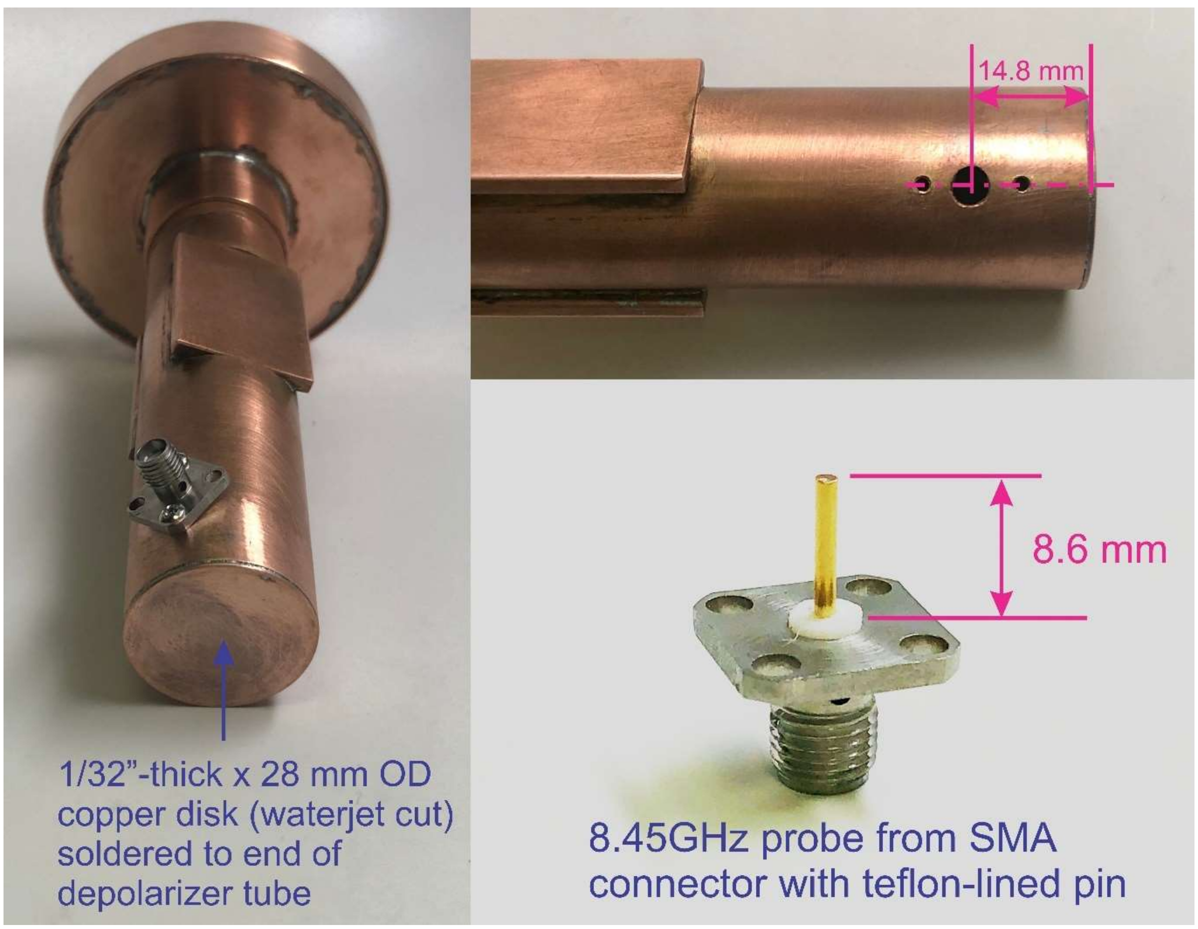


Figure 26 – The X-band probe is made from a long-stem SMA connector with most of the insulation removed and cut to ¼ λ

Later, in preparation of the EMM launch, KC2TDS kindly helped me add an RHCP port to be able to receive the spacecraft's LHCP transmissions. The dual-port feed is shown in Figure 27.

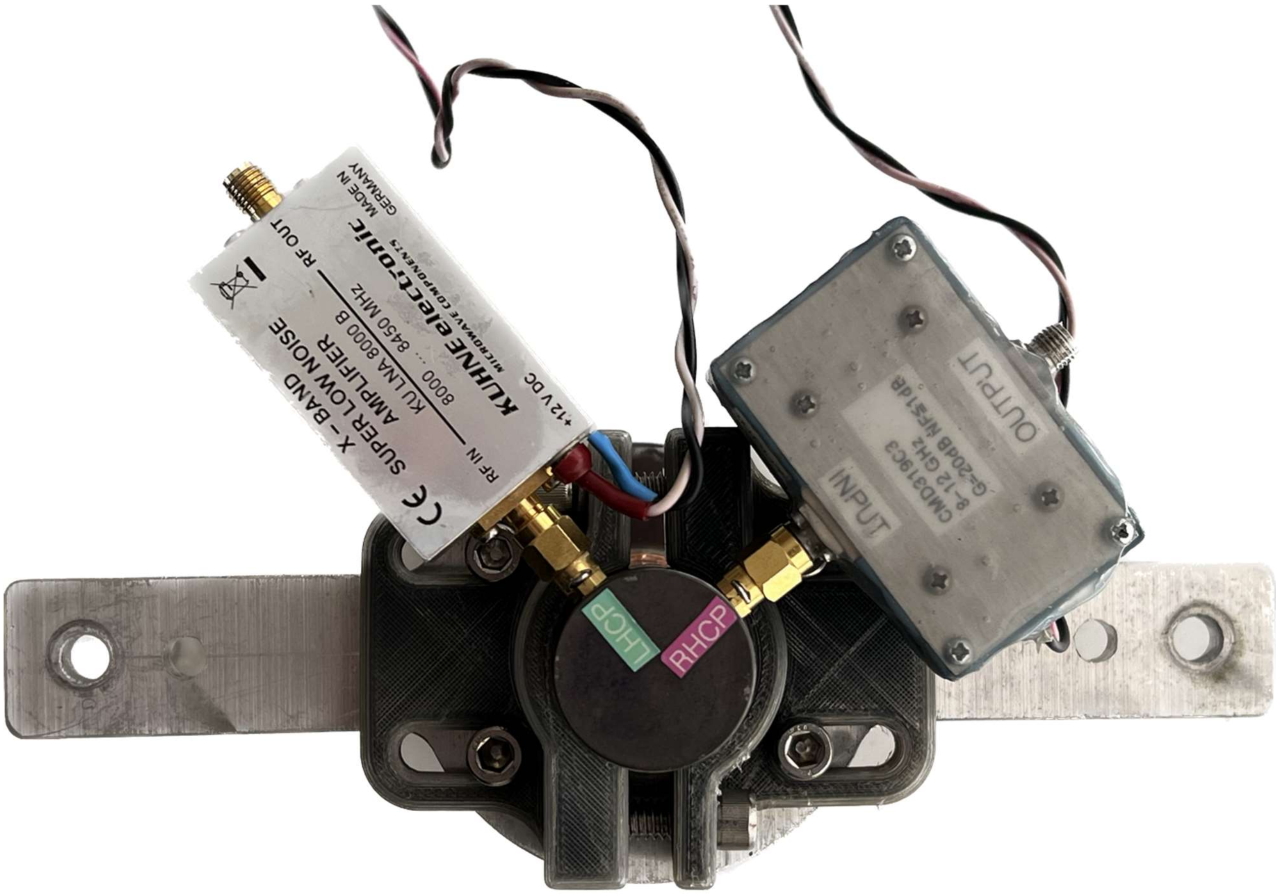


Figure 27 –RHCP and LHCP probes added by KC2TDS to squeeze-tube depolarizer feed built by M0EYT. Polarization refers to the feed, and is opposite to the polarization of the signal input to the dish.

The placement of the probe is critically important because that is what defines the received polarization. Figure 28 shows the orientation of the probes as seen from the feed's aperture to receive either left- or right-handed polarization. An LHCP feed is needed to receive the RHCP signals transmitted by the vast majority of DSN spacecraft (when operating nominally). This is because when the feed is mounted on a parabolic antenna, the spacecraft's RHCP signal becomes LHCP after being reflected by the dish.

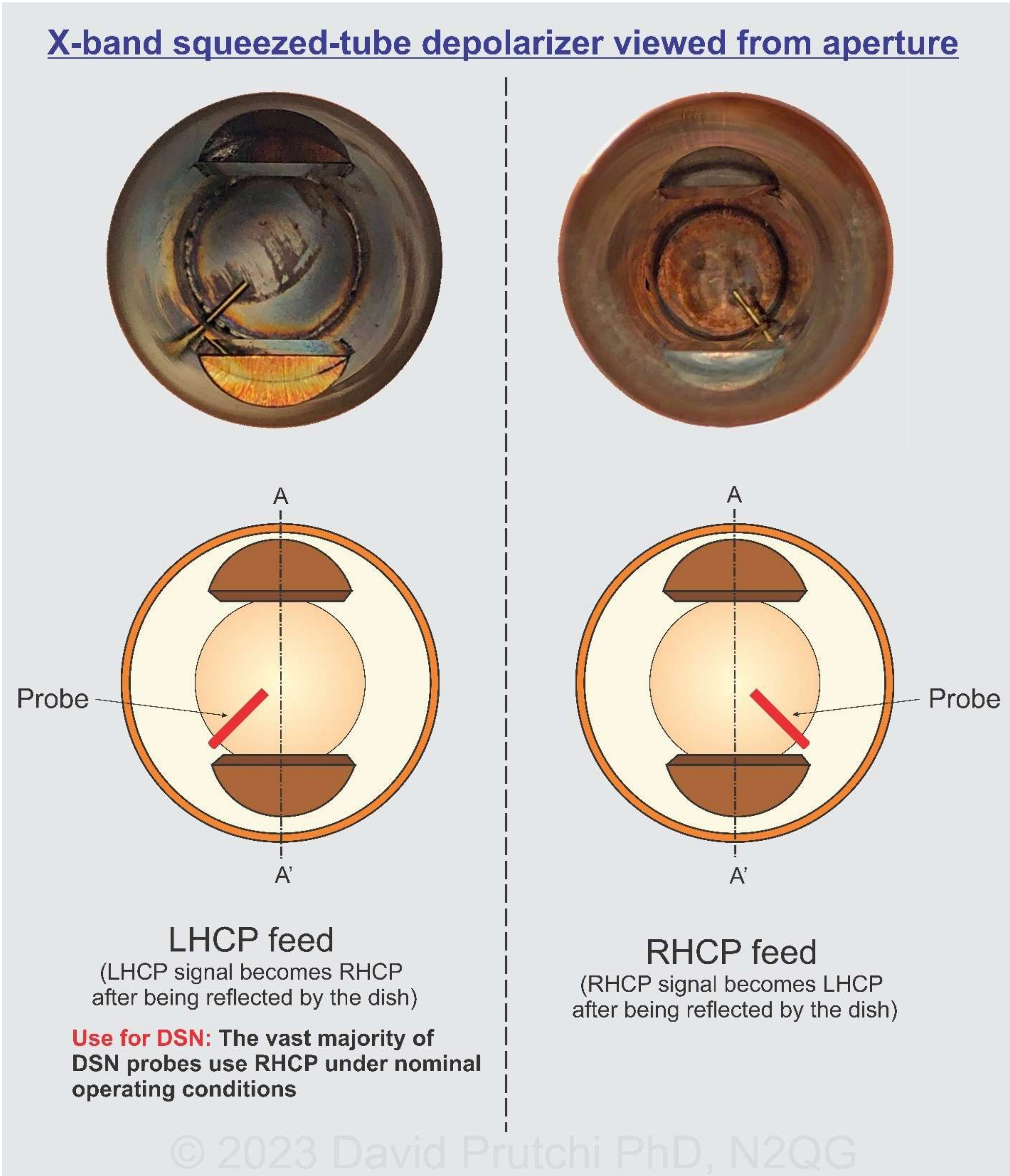


Figure 28 – Orientation of the ¼ λ probe within the depolarizer feed as seen from the aperture.

Most deep-space probes transmit in right-handed polarization. The Emirates Mars Mission, along the Voyager spacecraft are exceptions because they transmit in left-handed polarization. As the DSN band is crowding around planets, I expect more probes to use LHCP to prevent interference.

My system supports both RHCP and LHCP, and Figure 29 shows the importance of proper polarization setting. Of course, you could choose not to depolarize, and just use a linear probe, at the cost of 3dB, but as also seen in this figure, this is often out of the question when trying to detect distant probes.

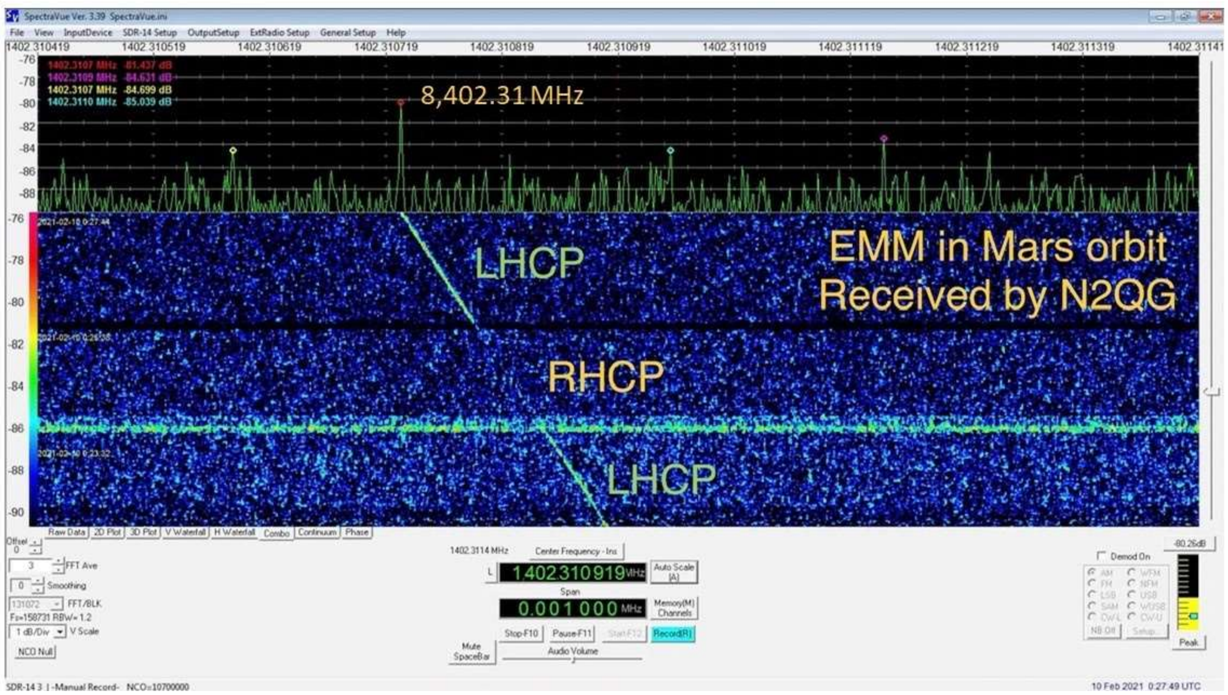


Figure 29 – This figure demonstrates de importance of selecting the correct polarization when receiving deep-space spacecraft.

9.3 Feed – Lessons Learned

A helical feed is a simple solution for S-band. At some point I want to experiment with a patch antenna.

For X-band, the squeezed-tube depolarizer and super Kumar scalar ring is definitely the way to go. If built right, the quality of polarization is excellent.

I'm also following closely the experiments that are being done with POTY-like dual-band feeds like those used for QO-100 so that I can have simultaneous S- and X-band capabilities on the 3.5m dish.

10 LNA

10.1 S-Band LNA

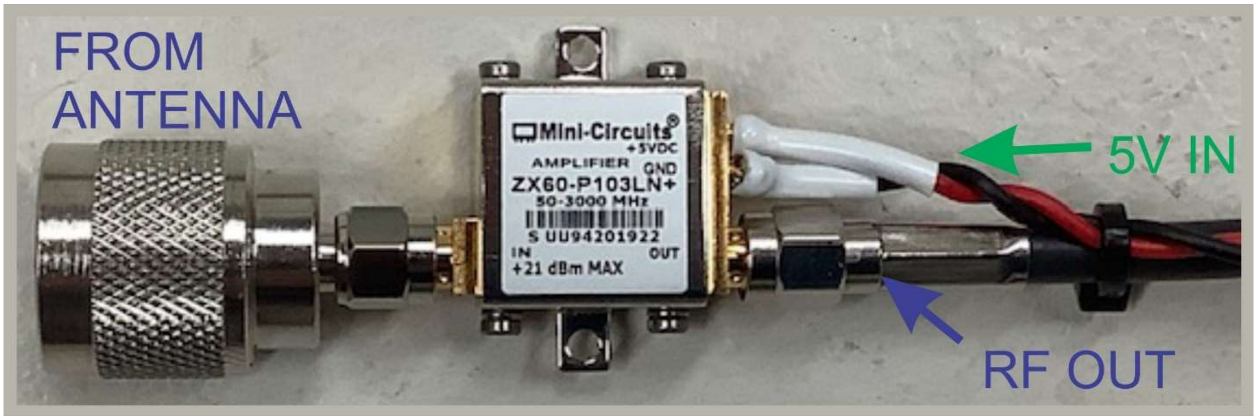


Figure 30 – S-band LNA can be mounted directly on the feed.

Since the LNA needs to be placed right at the antenna feed, I chose the 30 – 3,000 MHz E-PHEMT-based Mini-Circuits ZX60-P103LN+ ($114 new) with the following specs (at 2 GHz):

- Noise figure: 0.6 dB
- Gain: 10 dB
- Output power @ 1 dB compression: 2 dBm
- Output IP3: 6 dBm
- Input VSWR: 1.48 dB
- Output VSWR: 2.36 dB
- Isolation gain: 6.99 dB
- DC supply: 5V @ 95 mA

An SMA-to-N adaptor makes it possible to mount the LNA directly to the antenna. I put the whole assembly inside thick heat-shrink tubing, and then sealed it with RTV. After curing, I wrapped the whole assembly with pro-grade (30 mil) self-vulcanizing silicone tape for a weather-tight seal.

As shown in Figure 31 and Figure 32, the signal from the LNA is filtered by a surplus cavity filter meant for military telemetry operations. A second MiniCircuits ZX60-103LN+ is used as a gain stage and cable driver.

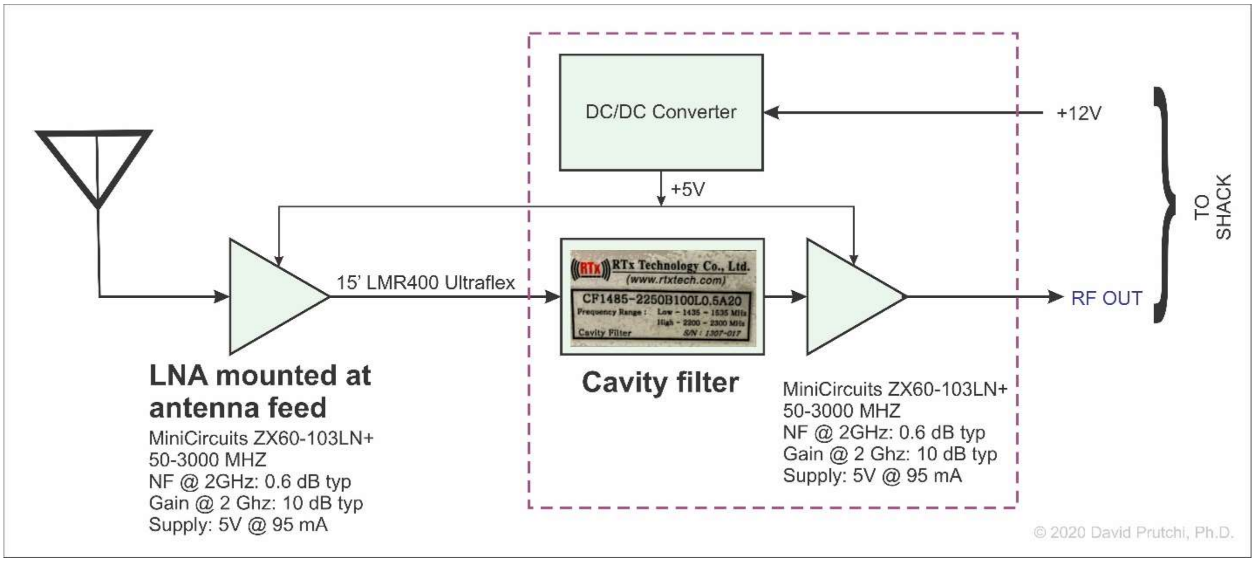


Figure 31 – S-band signals picked up by the helical feed are amplified by a MiniCircuits ZX60-103LN+ LNA and filtered by a surplus unit meant for military telemetry operations. A second MiniCircuits ZX60-103LN+ is used as a gain stage and cable driver.

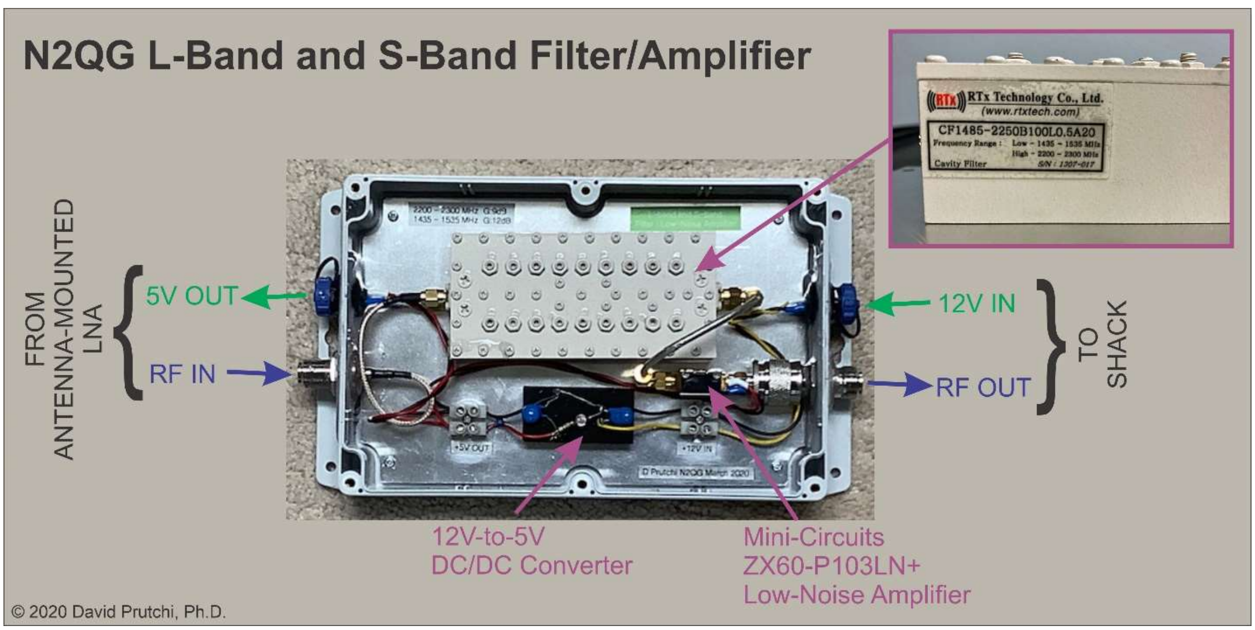


Figure 32 – The cavity filter, DC/DC converter, and cable driver of Figure 31 are enclosed in a weather-proof enclosure placed inside the control box for the 1.2 m dish.

My suburban location is full of signals which would interfere with S-band reception, so I needed a good filter. I found on eBay® the cavity filter shown in Figure 33 that seems to perfectly match the requirements for S-band DSN. It is made by RTx Technology in Korea.

Figure 33 – Surplus cavity filter The filter built for aeronautical and aerospace telemetry in the 1435-1535 and 2200-2300 MHz bands.

Decoding the filter's label is easy:

Table 5 – RTx Technology filter specs derived from label

Part Number	**CF of CD or C**D**	***	**B*****	**L*****	**A*****
Code	1) Cavity Filter Cavity Duplexer	2) Center Frequency	3) BandWidth	4) Insertion Loss	5) Attenuation
	CF	1,485-2,250	B100	L0.5	A20
Spec	**Type:** Cavity Filter	**Center Frequencies:** 1,485 MHz, 2,250 MHz	**Bandwidth:** 100 MHz	**Insertion Loss:** 0.5 dB	**Attenuation:** 20 dB

The filter is built for military telemetry operations, since the 1,435-1,535 and 2,200-2,300 MHz bands are allocated to aeronautical and aerospace telemetry. The band assignments covered by this filter are as follows:

L Band (1,435 to 1,535 MHz) – Aeronautical Telemetry and Mobile-Satellite Service:

This band is allocated in the US for government and non-government aeronautical telemetry use on a shared basis. The non-government use of this band is coordinated by the Aerospace and

Flight Test Radio Coordinating Council (AFTRCC). The frequencies in this range are assigned for aeronautical telemetry and associated remote-control operations for testing of manned or unmanned aircraft, missiles, rocket sleds, and other vehicles or their major components. Authorized usage includes telemetry associated with launching and reentry into the Earth's atmosphere, as well as any incidental orbiting prior to reentry of manned or unmanned vehicles undergoing flight tests. The following frequencies are shared with flight telemetering mobile stations: 1,444.5, 1,453.5, 1,501.5, 1,515.5, 1,524.5, and 1,525.5 MHz.

- 1,435 to 1,525 MHz. This frequency range is allocated for the exclusive use of aeronautical telemetry in the US.
- 1,525 to 1,530 MHz. Is now primarily a Mobile-Satellite Service. The Mobile Service (includes aeronautical telemetry) is now a secondary service in this band.
- 1,530 to 1,535 MHz. The Maritime Mobile-Satellite Service is a primary service in the frequency band from 1,530 to 1,535 MHz. The Mobile Service (including aeronautical telemetry) is a secondary service in this band.

S Band (2,200 to 2,300 MHz) – Space operations:

- 2,200 to 2,290 MHz. These frequencies are shared equally by the US Government's fixed, mobile, space research, space operation, and Earth exploration-satellite services. These frequencies include telemetry associated with launch vehicles, missiles, upper atmosphere research rockets, and space vehicles regardless of their trajectories.
- 2,290 to 2,300 MHz. Allocations in this range are for the space research service (deep space only) on a shared basis with the fixed and mobile (except aeronautical mobile) services.

10.2 X-Band LNA

My favorite LNA is the Kuhne KU LNA 8000 B Super Low Noise Amplifier (Figure 34). This is a professional-grade amplifier with extremely low noise (Table 6), designed specifically for DSN reception.

Figure 34 - Kuhne KU LNA 8000 B Super Low Noise Amplifier. Image credit: Kuhne Electronic

Table 6 – Manufacturer's specification of the Kuhne KU LNA 8000 B Super Low Noise Amplifier

Frequency range	8000..8450 MHz
Noise figure @ 18 °C	typ. 0.8 dB
Gain	min. 28 dB
Maximum input power	1 mW
Output power (P1dB)	typ. 31,6 mW (+15 dBm)
Output IP3	typ. 25 dBm
Input return loss (S11)	min. 10 dB
Supply voltage	+12 ... 15 V DC
Current consumption	typ. 90 mA
Operating case temp. range	-20 ... +65°C
Input connector / impedance	SMA-female, 50 ohms
Output connector / impedance	SMA-female, 50 ohms
Case	milled aluminum
Dimensions (mm)	50 x 30 x 17
Weight	45 g (typ.)

However, once I modified my downconverter to accept signals from a dual-polarization feed, I needed a second LNA. Not wanting to spend ~€450 on a second Kuhne LNA, I decided to roll my own based on the Qorvo CMD319C3 8-12 GHz ultra-low noise amplifier MMIC and their reference design. As shown in Figure 35, the home-brew LNA behaves very well compared to the Kuhne LNA.

Figure 35 – Comparison of signals received from the same spacecraft using Kuhne KU-8000-B LNA versus homebrew LNA based on Qorvo CMD319C3.

A low-cost ($150), but high-performance ultra-low-noise amplifier alternative is the L4-2ULNA made by Down East Microwave is shown in Figure 36 (https://www.downeastmicrowave.com/product-p/l4-2ulna.htm).

L4-2ULNA

SPECIFICATIONS

Noise Figure:	0.8 dB nominal
Gain:	22 dB nominal
Frequency Range:	8.1-8.6 GHz
Input Voltage:	7 - 16 VDC
Current Drain:	< 50 mA.

Figure 36 – Low-cost, high-performance LNA suitable for amateur DSN work.

10.3 LNA – Lessons Learned

S-band is most commonly used for communicating with spacecraft at relatively short distances, so there are many low-cost modules with suitable performance.

For X-band, I'm extremely satisfied with the performance of the Kuhne KU LNA 8000 B Super Low Noise Amplifier. However, it is not the only alternative out there. The DEMI LNA, as well as home-brewed units can work equally well at much lower cost.

11 Downconverter

11.1 S-band

I don't use a downconverter for S-band since my main receiver is an AOR AR-5000 (Figure 42), which covers 10 kHz to 2.6 GHz. Table 7 shows some of the medium-range and high-end SDRs that can also directly receive S-band signals.

Table 7 – SDRs that can directly receive S-band signals

SDR	Frequency Range	Resolution	External Reference
ADALM Pluto	325MHz to 3.8GHz	12-bit	No. Can be added
HackRF One	1 MHz to 6 GHz	8-bit	Yes. 10 MHz
Ettus USRP B200	70 MHz to 6 GHz	12-bit	Yes. 10 MHz
Nuand bladeRF 2.0 micro	47MHz to 6GHz	12-bit	Yes. 10 MHz default, but any up to 400 MHz

11.2 X-band

For my first downconverter I used a MiniCircuits mixer and a Hertley CTI MVSR-7320 Dual-Loop PLL synthesized oscillator as the LO. The Hertley unit performs superbly, and since its reference is 10MHz, it is easy to interface to a GPSDO. However, I wanted to mount the downconverter at the already heavy feedpoint of my 3.5m dish, so I decided to look for a lighter option. With that in mind, I decided to develop my downconverter around a DS Instruments MX12000 Integrated-LO Mixer. The block diagram of the first version of the "N2QG downconverter" is shown in Figure 37.

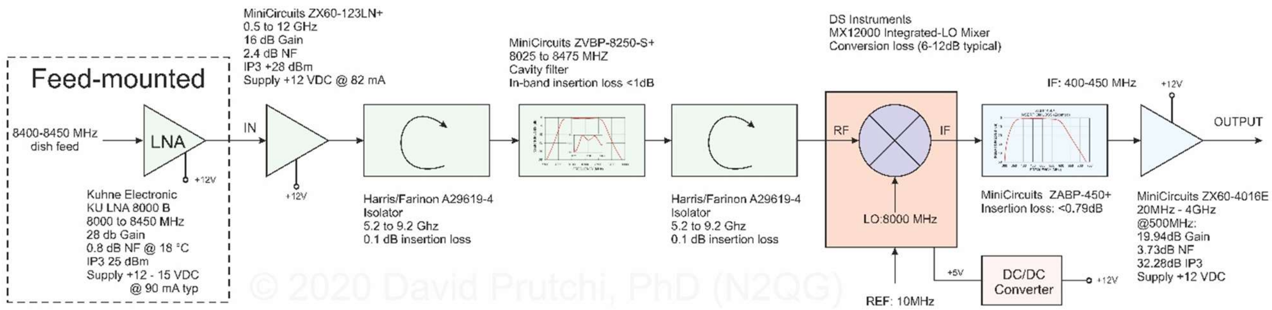


Figure 37 – Block diagram of the initial version of my downconverter.

In this setup, signals amplified by the Kuhne X-band LNA are sent to the downconverter's input over a short run of low-loss coax cable. Inside the downconverter, signals are further amplified by a MiniCircuits ZX60-123LN+ LNA before they are filtered by a MiniCircuits ZVBP-8250-S+ 8,025 to 8,475 MHz cavity filter. Two Harris/Farinon A29619-4 are used to isolate the input and output of the filter. The filtered signals are downconverted by the DS Instruments MX12000 Integrated-LO Mixer. With the LO programmed to 8.0 GHz, the output range is 400-450 MHz. Image products are rejected by a MiniCircuits ZABP-450+ 400-450 MHz band-pass filter, the output of which is buffered with a MiniCircuits ZX60-4016E amplifier that drives 100 ft of LMR-400 coax cable to the shack. We tested the downconverter (without LNA) at MUD2019, and measured a 4.58 dB noise figure and a downconversion gain of 24.4 dB

In July 2020 I brought home my work's Noise Figure Meter in order to look at the downconverter more closely to improve NF. The improved configuration is shown in Figure 38. As shown in Figure 39, my measurements from the input of the LNA to the output of the downconverter's IF filter (no output buffer) are Gain=36.5 dB and NF=1.02 dB, which compare very well with those of the Kuhne LNC 8084A downconverter (which is no longer available).

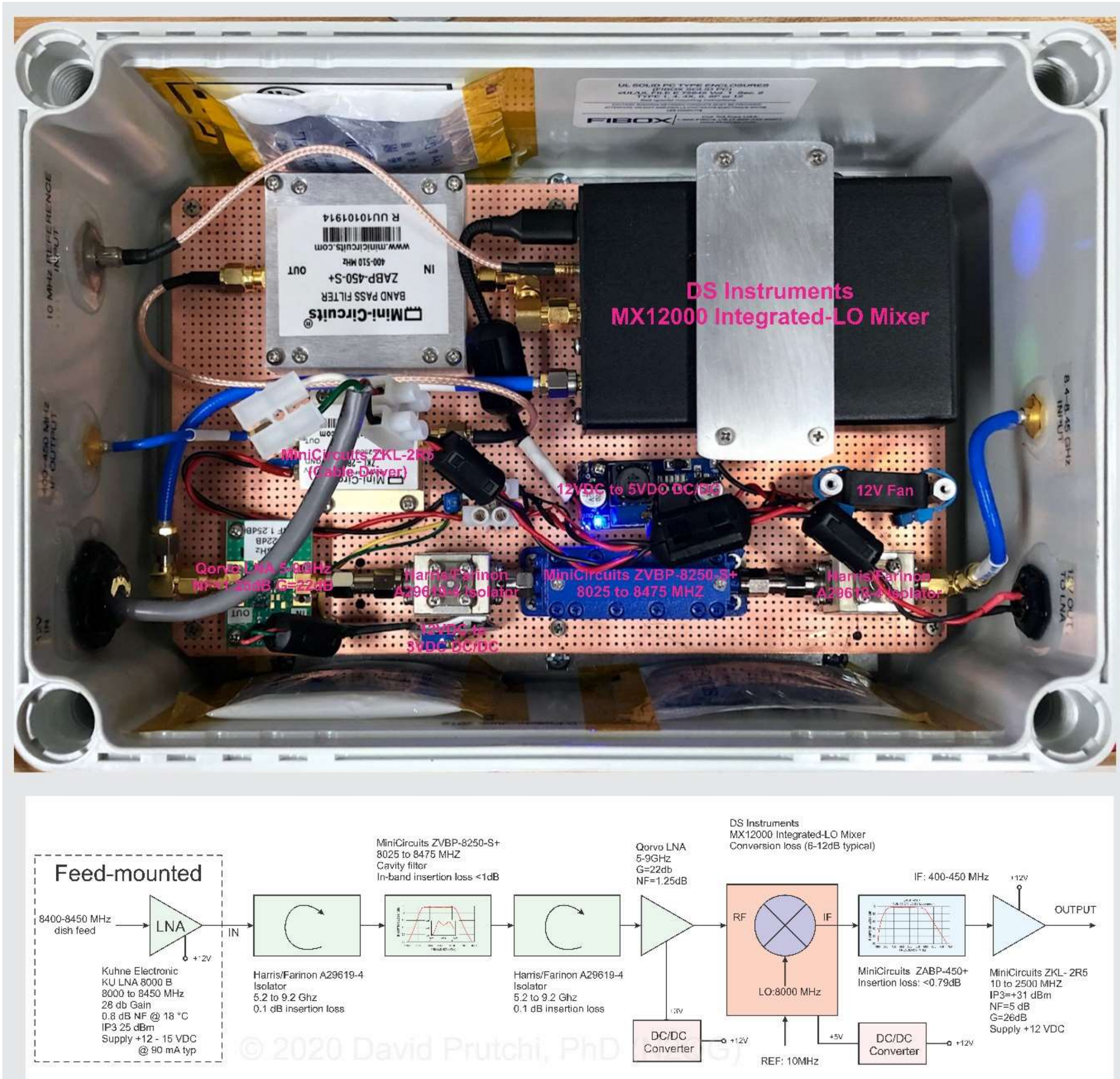


Figure 38 – Block diagram of the improved X-Band DSN downconverter (as modified July 2020)

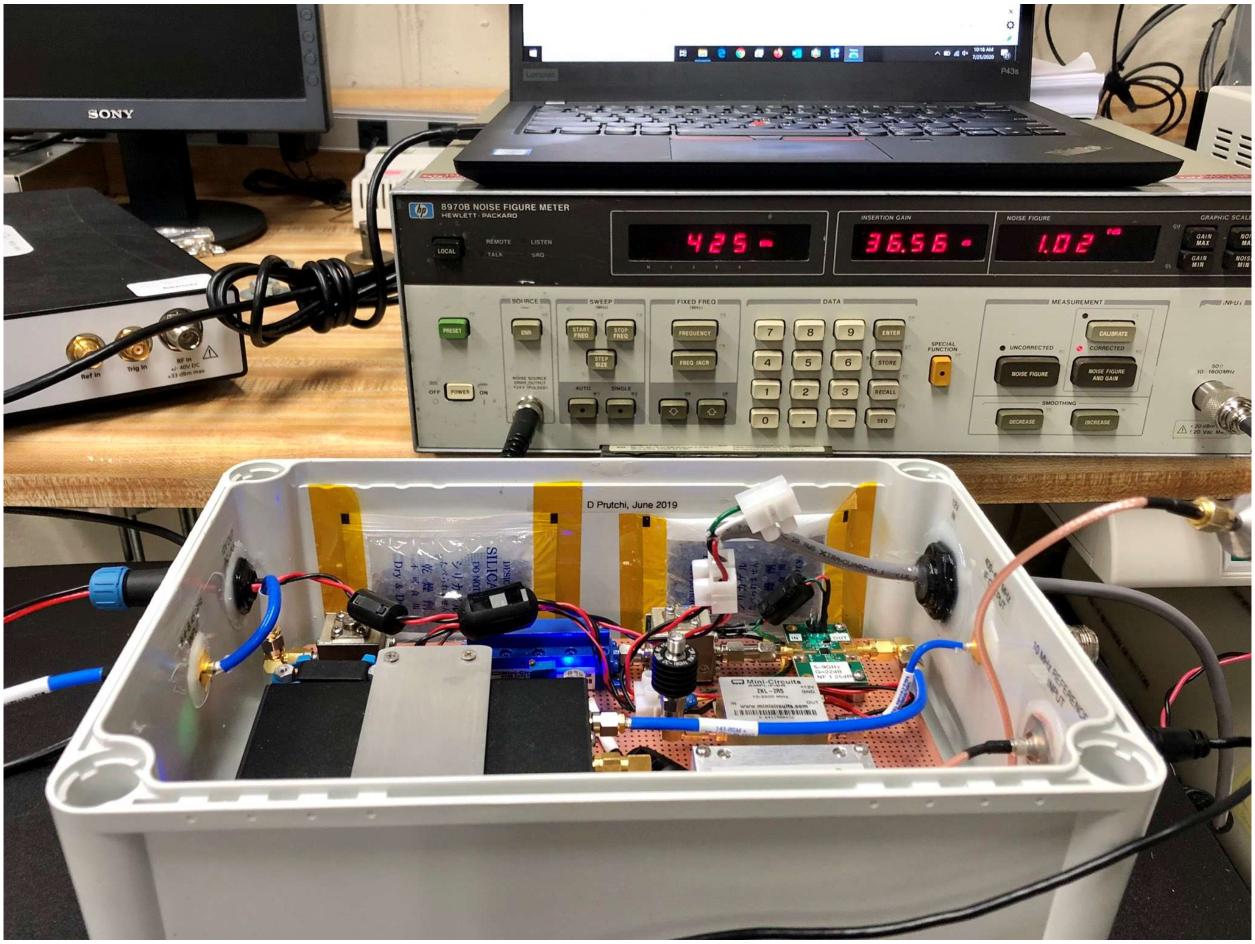


Figure 39 – Measurement of NF and gain of July 2020 version of the N2QG downconverter. Measurements are all the way from the input of the LNA to the output of the downconverter.

I later added another input connector and a coaxial relay so that I can select whether to downconvert the signal coming from the RHCP or the LHCP LNAs. I also added a second downconverter chain to cover the 7,250 to 7,750 MHz MilSat band. I can now select the polarization and band remotely from my shack. Additionally, I used LOs such that downconverted signals are in the 1,250-1,500 MHz range. My current downconverter's schematic is shown in Figure 40 and its construction and mounting are shown in Figure 41.

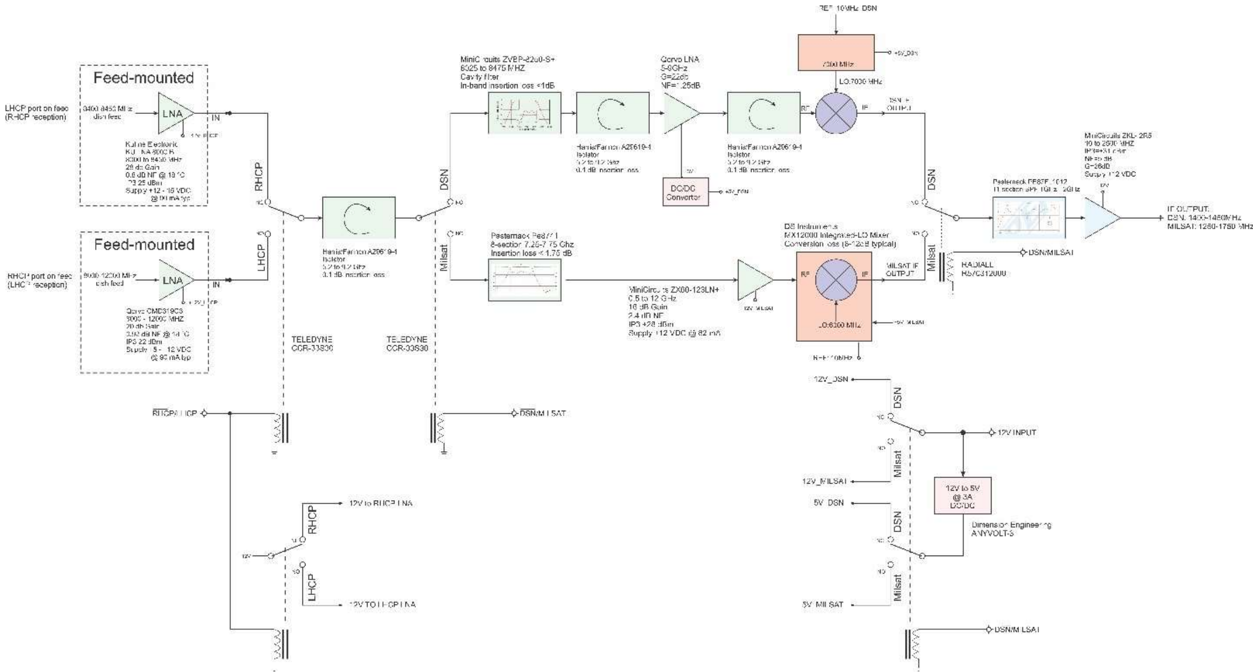


Figure 40 – Schematic diagram of my X-band dual-polarization, dual-band downconverter.

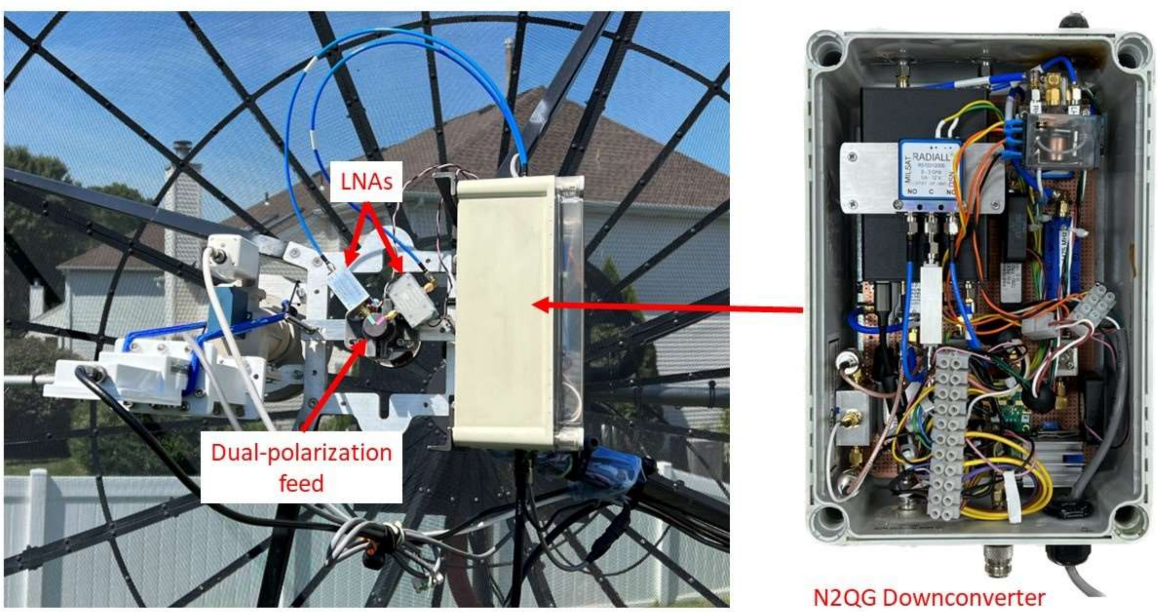


Figure 41 - X-band dual-polarization, dual-band downconverter mounted in close proximity of the LNAs (left). Internal view of downconverter (right)

11.3 X-Band Downconverter – Lessons Learned

I had the opportunity to test a Kuhne KU LNC 8085 C PRO downconverter. I did not like it. First of all, it drifts way too much for DSN work, so I had to modify it to accept an external 20 MHz reference. Kuhne realized this shortcoming, and released a new version (KU LNC 8085 C PRO2, listed at €579) that accepts a 10 MHz reference signal. Most importantly however, although it is a convenient, light-weight solution, received signals are much noisier than those yielded by my downconverter, and it is full of "birdies." I'm very satisfied with the performance of my downconverter, so I don't think that I'll be modifying it further.

12 Receiver and IF SDR

The receiver in my shack is an AOR AR-5000 (Figure 42). I LOVE this radio, and so do many of the Amateur DSN DXers because of its incredible reliability and performance. This is simply the best receiver I've ever owned. I use an external 10 MHz GPSDO as the frequency reference.

Its coverage is from 10 kHz to 2.6 GHz, so I can use it without a downconverter for S-band SatCom and to receive the lunar probes.

I feed the AR-5000's 10.7MHz IF to an RF-Space SDR-14, which I modified to accept an external GPS-disciplined 66.66 MHz reference. I use SpectraVue running under Windows 10 to control both the SDR-14 and the AR-5000.

Figure 42 – My AOR AR-5000 receiver and the RFspace SDR-14 that I use for IF sampling.

12.1 Receiver – Lessons Learned

The AOR AR-5000 and SDR-14, although long obsolesced by their manufacturers, are simply the best receiver/SDR combination I've ever used.

That said, I'm interested in becoming more proficient with GNURadio, as well as with STRF (Satellite Tracking Toolkit for Radio Observations) which runs under Linux. For this reason, I'm planning to add an Ettus USRP or a Nuand bladeRF SDR to my shack.

13 Software

13.1 Tracking

Knowing where to point the antenna is possible through the use of ephemeris data that can be downloaded from NASA JPL's HORIZONS System. As shown in Figure 43, the ephemeris data contain the right ascension and declination for the selected target spacecraft from which the antenna azimuth and elevation can be calculated. In addition, the relative velocity calculation is useful for determining the Doppler shift for the received signal.

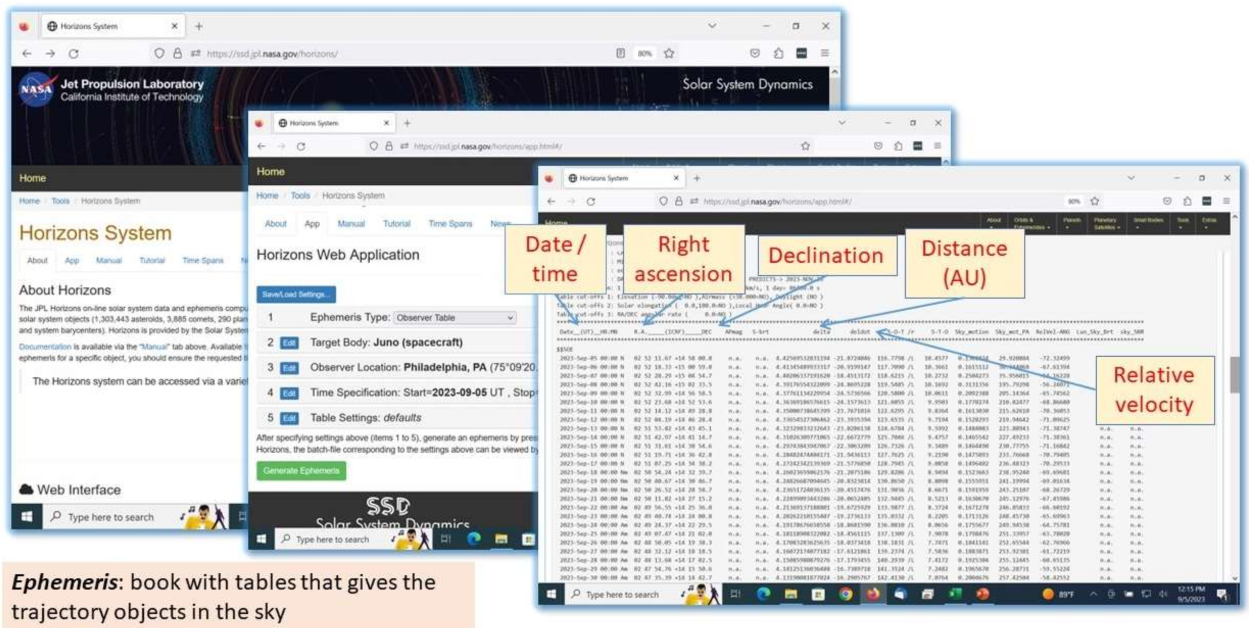


Figure 43 – Ephemeris data for deep-space spacecraft can be downloaded from NASA JPL's HORIZON system.

When I just started working on DSN, ephemeris data had to be downloaded from JPL's HORIZONS system and converted to a table that could be used by one of the tracking programs. Soon after however, Codrut Buda YO3DMU added a DSN feature to his PstRotator software which automatically downloads ephemeris data straight from NASA JPL's Horizons and uses it to control the rotator (Figure 44).

Although it lacks the neat graphics of Nova for Windows, I really like PstRotator because it is very well maintained. Codrut, its developer, is extremely responsive and helpful. Multiple instances of PsTRotator can run simultaneously, so I can control the 1.2m dish for DSN at the same time that I work EME or at a different DSN band on the 3.5m dish.

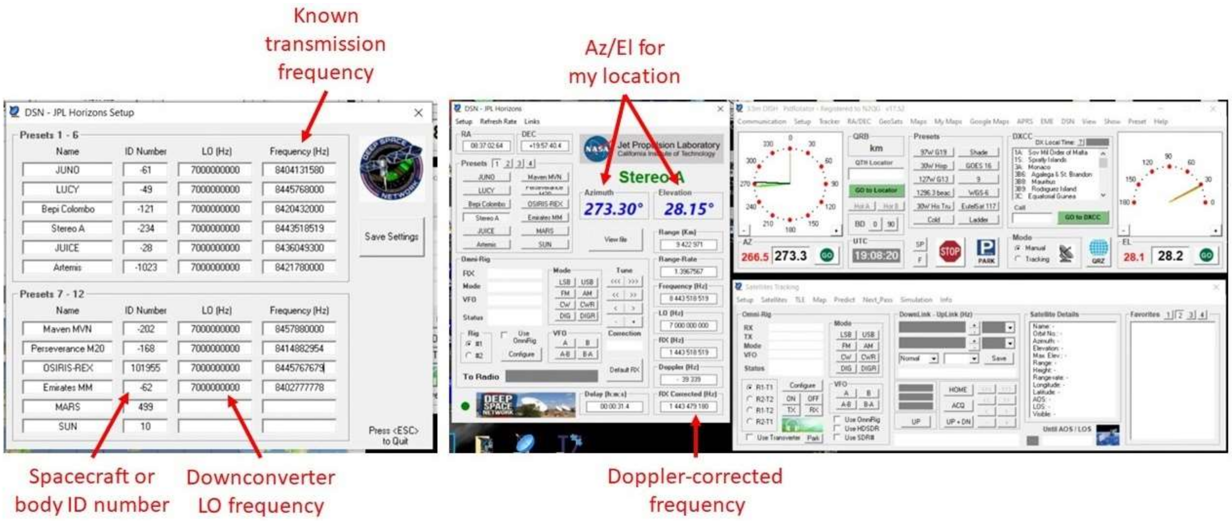


Figure 44 – PstRotator by Codrut Buda YO3DMU

13.2 Spectrum analysis

The main reason for still using the SDR-14 to sample the AR-5000's IF is to be able to use SpectraVue software, which is a favorite of many amateur DSN aficionados. The software is truly ideal for tweaking the system on Sun and Moon noise, and outstanding for displaying signals received from spacecraft.

That said, I've started using my AirSpy R2 and SDRplay RSP duo as receivers because they are directly supported by popular SDR packages, as well as by SatDump.

13.3 Demodulation and Decoding

Most DSN signals are too weak for receiving modulation sidebands. However, soon after launch, signals are usually strong enough that demodulation and decoding are possible. For example, Figure 45 shows a signal from Tianwen-1 which was decoded by Daniel Estevez. Through careful detective work he was able to determine what some of those telemetry channels represent. For example, the channel shown on the rightmost pane was found to correspond to rotation rate coming from a gyroscope on board the spacecraft.

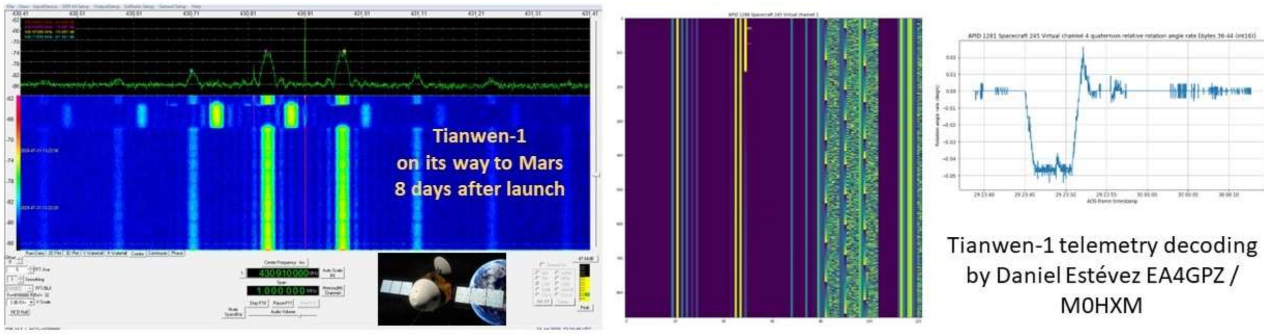


Figure 45 – Signals from Tianwen-1 soon after launch showed very strong modulation sidebands (left) which could be demodulated and decoded (right).

Sometimes, even video can be recovered from high-rate telemetry links as shown in Figure 46, where Jakub Hruška, AKA "r00t" decoded video from signals received by Paul Marsh (M0EYT) from the Chang'e 5 spacecraft on its way to the Moon and SpaceX's Falcon 9 telemetry downlink.

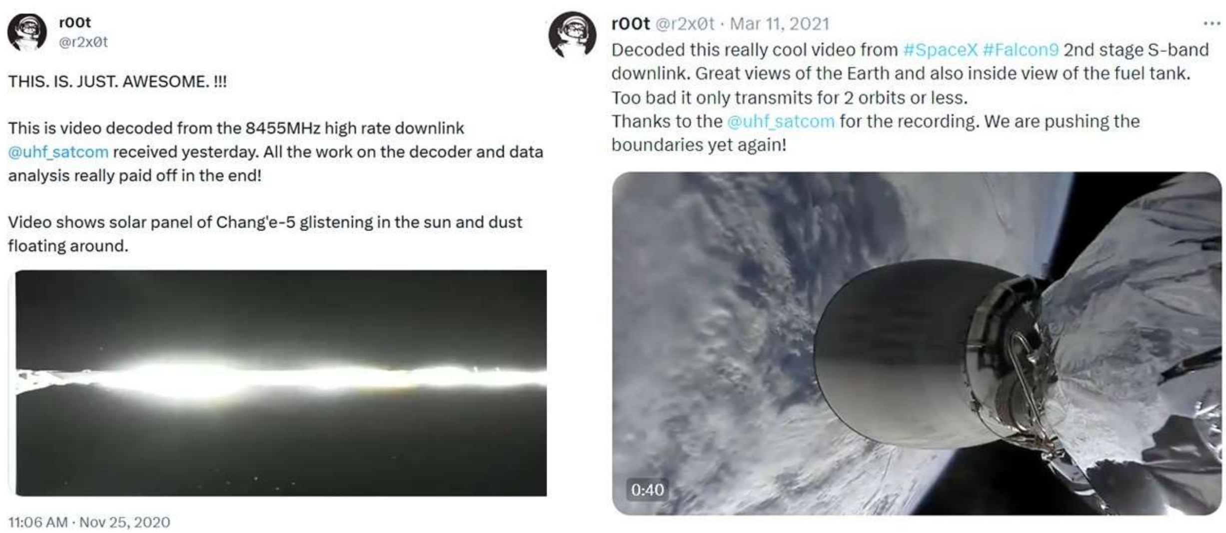


Figure 46 - Jakub Hruška, AKA "r00t" decoded video from signals received by Paul Marsh (M0EYT) from the Chang'e 5 spacecraft on its way to the Moon and SpaceX's Falcon 9 telemetry downlink. (Figures used with permission. Courtesy of Jakub Hruška).

On August 2023, the STEREO-A probe had its "inferior conjunction" with Earth which brought it as close as 9 million kilometers. Two spacecraft were launched in 2006 and placed in heliocentric orbits that caused one of them to pull ahead of Earth and one to fall behind (Figure 47). The idea was to be able to provide stereoscopic imaging of the sun for the study of coronal mass ejections. Contact with STEREO-B was lost in Sept. 2016. However, STEREO-A is alive and its strong signal is very easy to detect. Every 17 years its orbit brings it back close to Earth.

STEREO - (Solar TErrestrial RElations Observatory)

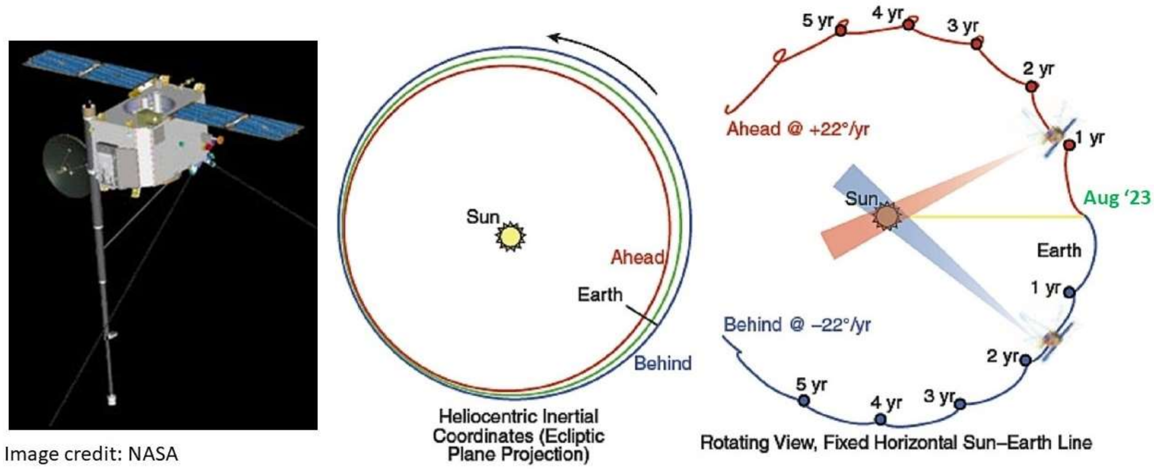


Figure 47 - Two spacecraft were launched in 2006 and placed in heliocentric orbits that caused one of them to pull ahead of Earth and one to fall behind. The idea was to be able to provide stereoscopic imaging of the sun for the study of coronal mass ejections. Contact with STEREO-B was lost in Sept. 2016. However, STEREO-A is alive and its strong signal is very easy to detect. Every 17 years its orbit brings it back close to Earth.

As shown in Figure 48, the conjunction gave Amateur DSN enthusiasts the opportunity to record very high-quality signals from the low-rate beacon at 8,443.5 MHz. The signals could be demodulated using SatDump and then converted into images using a decompressor found in between NASA's documentation.

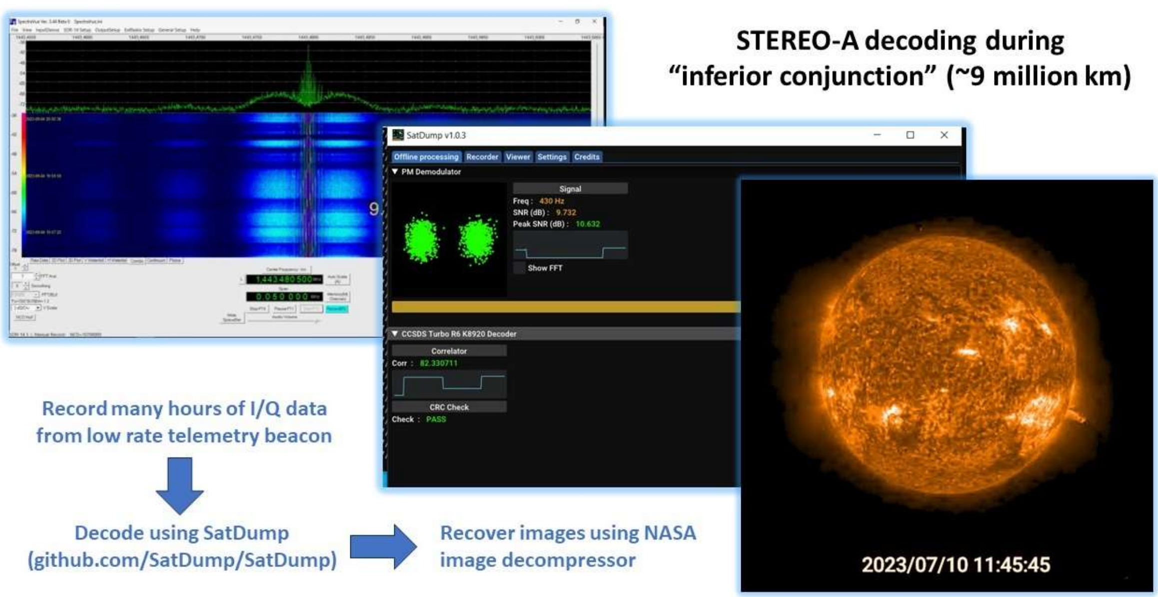


Figure 48 - On August 2023, the STEREO-A probe had its "inferior conjunction" with Earth which brought it as close as 9 million kilometers. This gave Amateur DSN enthusiasts the opportunity to record very high-quality signals from the low-rate beacon at 8,443.5 MHz. The signals could be demodulated using SatDump and then converted into images using a decompressor found in between NASA's documentation. Image decoded by Fred Jansen, Ph.D. (𝕏: @redplanet00), used with permission.

File names, and other ASCII data are often found when decoding spacecraft data. There was even an ASCII "easter egg" embedded in the Mars 2020 and Psyche telemetry (Figure 50).

```
N.Abcouwer P.Basa M.Belete E.Benowitz S.Brooks
J.Biesiadecki L.Burke D.Byrne S.Chen S.Scandore
J.Carsten K.Edelberg D.Gaines D.Leang R.Joshi
R.Haleski A.Harris L.Galdamez S.Lewis T.Litwin
D.Lam Q.Ho M.Maimone M.McHenry D.Morgan S.Myint
B.Martin P.Partikian G.Rabideau P.Romano R.Tsao
M.Schoppers A.Shearer R.Srisamang C.Williams
L.Stewart O.Toupet I.Trettel I.Uchenik V.Verma
P.Vieira E.Wang B.Wright G.Yang B.Cichy C.Pong
G.Reeves M.Tuszynski J.Casoliva P.Brugarolas
Z.Rahman G.Griffin T.Fouser M.Wang P.Kwan
A.Baez Harry *** The MSL FSW development team.

 There is beauty in space, it is orderly. There
 is no weather, and there is regularity. It is
 predictable. Just look at our little Explorer;
 you can set your clock by it. Everything in
 space obeys the laws of physics. If you know
 these laws, and obey them, space will treat
 you kindly.     -- Wernher von Braun

 Deep Purple '72 - Let's go Space Truckin'
```

Figure 49 - "Easter egg" decoded by Daniel Estévez from the Mars 2020 X-band telemetry soon after launch. Used with permission, kind courtesy of Daniel Estévez.

```
[24]: packets = list(ccsds.extract_space_packets(tm, 255, 63))

/home/daniel/contracting/Psyche/ccsds.py:93: UserWarning: [Space Packet extractor Spacecraft 255 VC 63] Broken stream. Last frame count 62697
8, current frame count 626982
  warnings.warn(f'[Space Packet extractor Spacecraft {sc_id} VC {virtual_channel}] Broken stream. Last frame count {frame_count}, current fra
me count {frame_count_new}')

[32]: all([p[ccsds.SpacePacketPrimaryHeader.sizeof():] == packets[0][ccsds.SpacePacketPrimaryHeader.sizeof():] for p in packets])

[32]: True

[35]: easter_egg = packets[0][ccsds.SpacePacketPrimaryHeader.sizeof():]
      easter_egg

[35]: b"A.Arslanian D.Beach M.Belete A.Bhosle Y.Brenman  \nD.Byrne R.Cheng P.Cheung M.Cisler D.Cummings     \nA.Dobrev P.Doronila B.Duckett D.Gaine
s L.Galdamez\nL.Hall S.Harris H.Hartounian D.Hecox Q.Ho        \nJ.Hofman Z.Hua C.Jones W.Kaye D.Kou S.Kroese     \nD.Leang L.Manglapus J.Mas
ci B.Morin R.Nemiroff   \nC.Oda J.Pavek V.Reddy J.Sawoniewicz              \nA.Shearer L.Stewart G.Sun J.Thoma D.Tran R.Tsao  \nM.Tuszynski
I.Uchenik M.Wade V.Wong R.Woo M.Yang \nW.Yasin H.Yun ** Rohan the Destroyer b.12/9/21 **\n        @@&J!~...       ^$$~       ^JPG@@@        \n
@#7!: .       ..~$$~     ^Y ~PP@@        \n        &77:..      :$$J: '     .5:  !##@        \n        Y!~.:      !J^ ~P ''    J5    G#&
\n        77:    !. !Y:   ~7!!7JY^^!Y   $&#        \n        77:    !.:5!          :^. ~~   $##        \n        5!~    ~:!5J777$$!
G#&        \n        @$7^    .^!JJJ$:5P.       ^^ $##@        \n        @&J$^      :.   YG.     .:J7J##@@        \n        @@@5$!.    :..  P
&.   ^.!!!L.Park        \n            This spacecraft is equipped          \n    with the latest ABS and pDMA technologies   \n"

[37]: print(str(easter_egg, 'ascii'))

A.Arslanian D.Beach M.Belete A.Bhosle Y.Brenman
D.Byrne R.Cheng P.Cheung M.Cisler D.Cummings
A.Dobrev P.Doronila B.Duckett D.Gaines L.Galdamez
L.Hall S.Harris H.Hartounian D.Hecox Q.Ho
J.Hofman Z.Hua C.Jones W.Kaye D.Kou S.Kroese
D.Leang L.Manglapus J.Masci B.Morin R.Nemiroff
C.Oda J.Pavek V.Reddy J.Sawoniewicz
A.Shearer L.Stewart G.Sun J.Thoma D.Tran R.Tsao
M.Tuszynski I.Uchenik M.Wade V.Wong R.Woo M.Yang
W.Yasin H.Yun ** Rohan the Destroyer b.12/9/21 **
        @@&J!~...       ^$$~       ^JPG@@@
        @#7!: .       ..~$$~     ^Y ~PP@@
        &77:..      :$$J: '     .5:  !##@
        Y!~.:      !J^ ~P ''    J5    G#&
        77:    !. !Y:   ~7!!7JY^^!Y   $&#
        77:    !.:5!          :^. ~~   $##
        5!~    ~:!5J777$$!            G#&
        @$7^    .^!JJJ$:5P.       ^^ $##@
        @&J$^      :.   YG.     .:J7J##@@
        @@@5$!.    :..  P&.   ^.!!!L.Park
            This spacecraft is equipped
    with the latest ABS and pDMA technologies
```

Figure 50 – "Easter egg" decoded by Daniel Estévez from the Mission to Psyche X-band telemetry soon after launch (October 14, 2023). Used with permission, kind courtesy of Daniel Estévez.

The window of opportunity to decode signals after launch is usually very narrow because the spacecraft's low-gain antenna (LGA) is used to reduce the need for precise tracking during the early phases of the trip, as well as not to saturate NASA/ESA's sensitive receivers on the ground. This means that signals quickly start to weaken in the weeks after launch, often to the point that their residual carrier is barely visible. The spacecraft's high-gain antenna (HGA) usually starts to be used once the probe is some 5-7 million kilometers away from Earth, which sometimes opens a second window of strong, decodable signals.

13.4 Software – Lessons Learned

My next step in the hobby is to be able to analyze the signals that I receive to understand the orbital dynamics of the spacecraft. STRF, written by Cees Bassa is a satellite tracking toolkit for radio observations (RF) designed to analyze the Doppler curves of satellite signals to identify satellites and/or determine their orbits.

The software is designed for Linux operating systems, and will work with most software defined radios supported by GNUradio. The software comes with tools for data acquisition, performing FFTs to generate timestamped spectrograms (waterfall plots), and analysis, to extract and analyze Doppler curves to derive the orbital dynamics of spacecraft.

This is an interesting field, especially when trying to figure out what less-than-open space agencies are trying to do. For example, China did not disclose in advance the entire mission timeline and major milestones for Chang'e 5. Its service module was moved into the Earth-Moon L2 Lagrange Point in late November 2021, but it was a surprise when it suddenly left L2 point.   Scott Tilley, using data from various amateur observers was able to figure out that China sent the service module into Distant Retrograde Orbit of the Moon (Figure 51), which is the first time anyone had used this orbit.

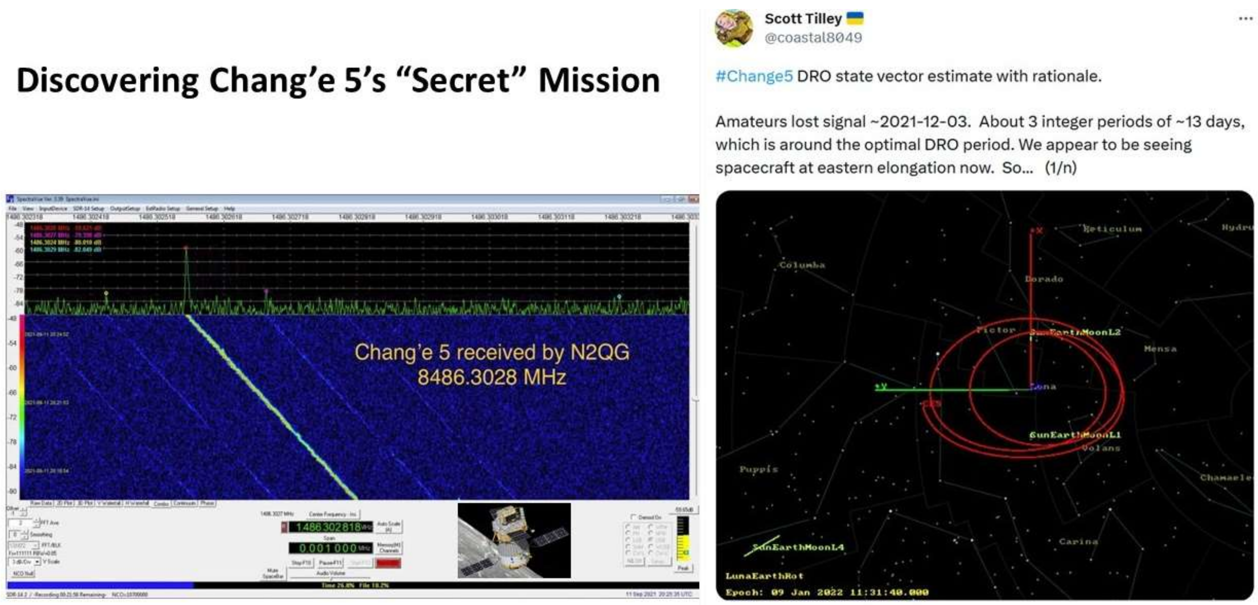


Figure 51 – Scott Tilley (VE7TIL) using data from various amateur observers was able to figure out that China sent the Chang'e 5 service module into Distant Retrograde Orbit of the Moon, which is the first time anyone had used this orbit. Figure used with permission, kind courtesy of Scott Tilley.

The other area in which I'm interested is in demodulating and decoding these signals. EA4GPZ ran a GNURadio workshop exactly on this topic. I recently set up my signal analysis computer to run as a dual-boot system, with Windows for SpectraVue and DragonOS to run GNUradio, SatDump, and STRF.

14 System Calibration

A lot of time in this hobby goes into tweaking the antenna to make it possible to receive very weak signals. The Sun and Moon are the preferred sources of broadband noise to peak and benchmark systems (Figure 52).

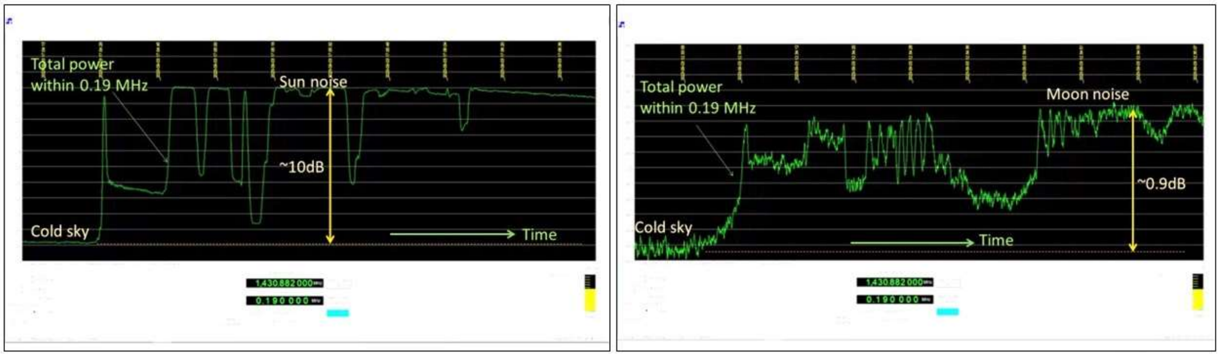


Figure 52 – Sun and Moon noise detected by my X-band system using the 3.5 m antenna. These measurements are excellent for benchmarking against other systems. These measurements show that my 3.5m dish underperforms for a dish of this size.

Now, antenna diameter is not the only determinant of gain. The type of dish, surface accuracy, and illumination by the feedhorn are extremely important. The best Sun noise I've managed to get from my perforated mesh 3.5m C-band TV dish is 11 dB above cold sky, which is what I would expect from maybe a 2.4 m solid telecom-grade dish. It is very likely that I lose a few dB because of the shadow caused by all the stuff that I have at the feed.

As a reference, M0EYT who holds the DX record for a dish in this range achieves ~14 dB Sun and ~1.25 dB Moon noise on his almost 3 m diameter telecom-grade solid dish. There is nevertheless a tradeoff with other uses for the antenna because, for example, my dish behaves really well for EME at 1296 MHz.

Geostationary satellites that transmit in the military portion of X-band are another very useful tuning tool, especially to calibrate the rotator. This is the main reason why I added a dedicated 7.25 – 7.75 GHz section in my downconverter. Figure 53 shows the beacon from Anik G1, which is a multi-purpose Canadian satellite, and the Wideband Global SATCOM 6 satellite operated by the US Air Force. I calibrate my rotator to peak on these signals when pointing at their fixed locations in the sky.

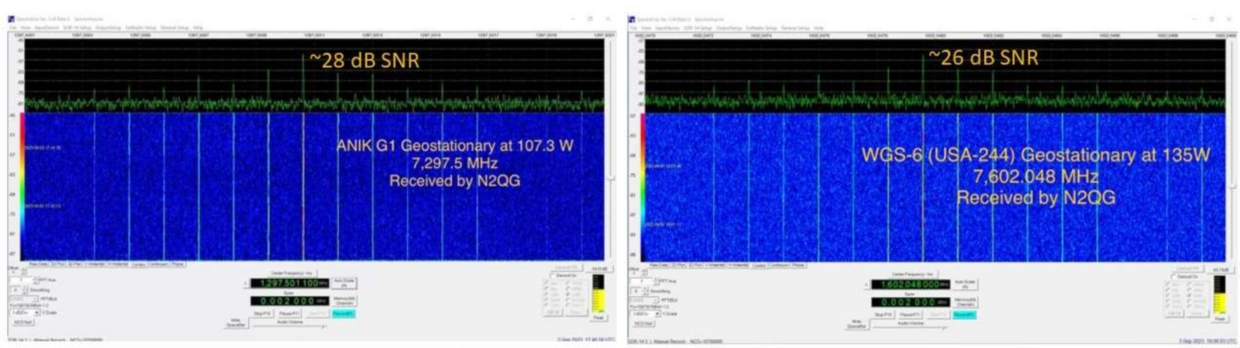


Figure 53 – The military X-band beacons from geostationary satellites are excellent sources for calibrating rotators.

15 Amateur DSN DX

15.1 S-band

Figure 54 shows some of the spacecraft that I've received using the helical feed mounted on the 1.2m dish. Most of the spacecraft transmitting in S-band are Lunar probes or orbiting the Lagrangian points, so they are not especially challenging.

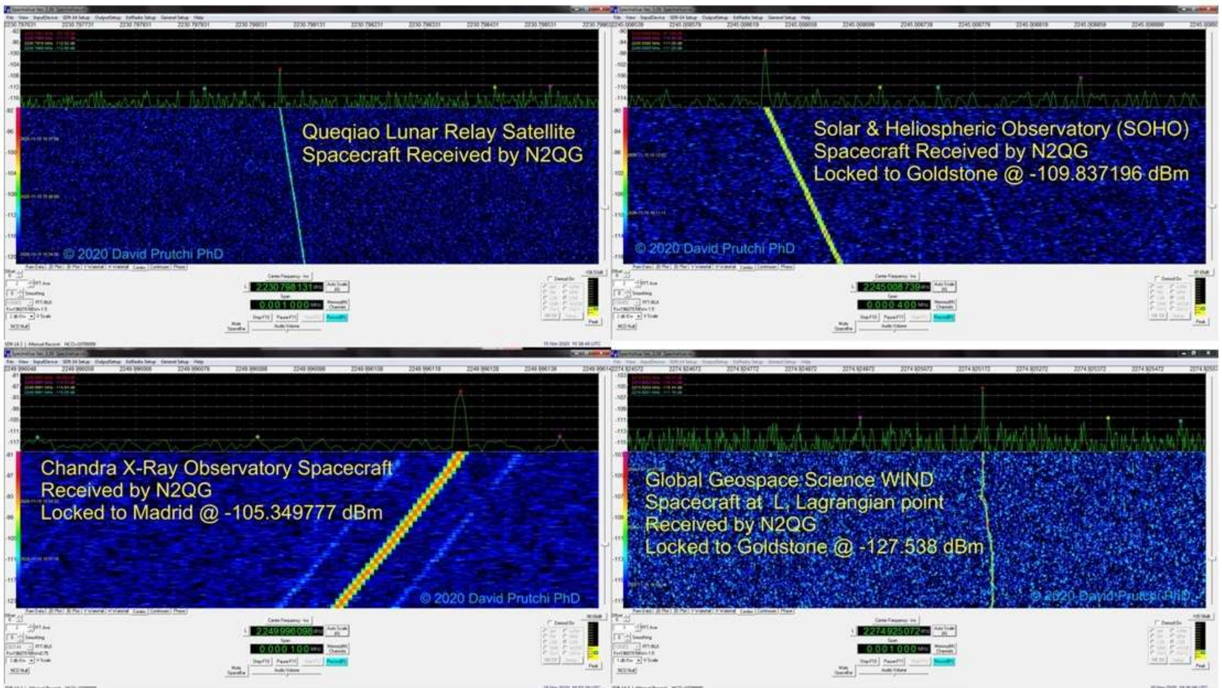


Figure 54 – Some of the spacecraft that I have received in S-band using the 1.2m dish with helical feed

15.2 X-band

X-band is where the real DX lies. Figure 55 shows some of the spacecraft that I received when I started with X-band DSN. In the lower-right pane of this figure is ESA's Mars Express spacecraft orbiting Mars. It's interesting to note that it is not common for Martian landers and rovers to communicate directly with Earth. Instead, they communicate with one of the orbiters that acts as a relay to Earth. They do so in addition to their primary mission. As shown in Figure 56, the current relay network comprises Mars Odyssey launched in 2001, Mars Reconnaissance Orbiter (MRO) launched in 2005, MAVEN launched in 2013, and ESA's Trace Gas Orbiter launched in 2016.

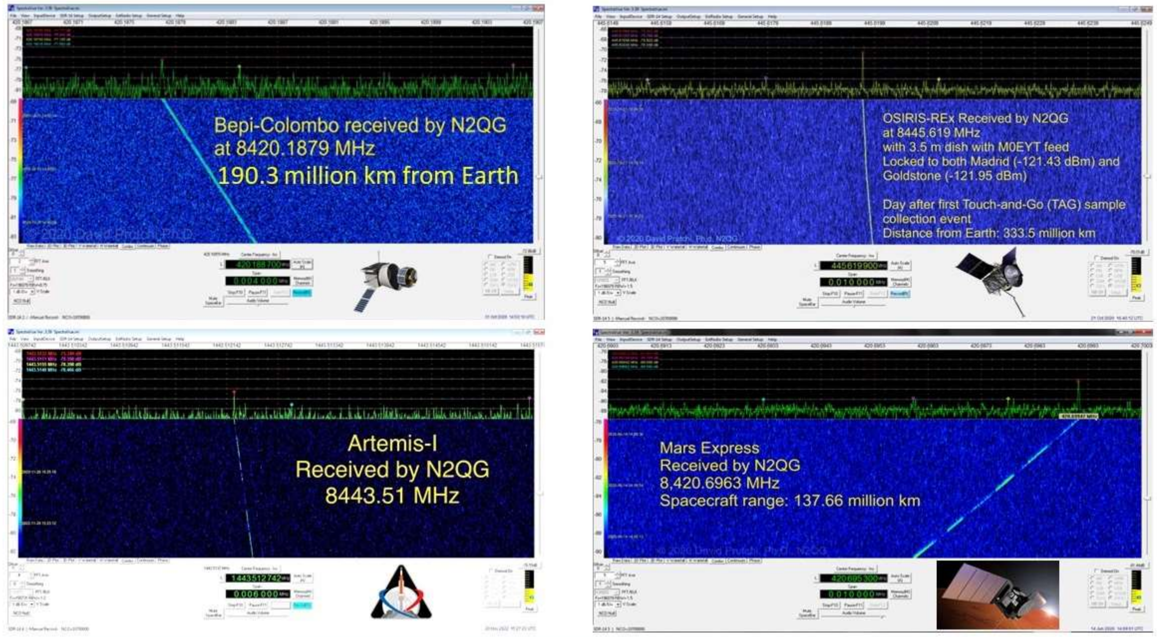


Figure 55 - Some of the spacecraft that I received when I started with X-band DSN included Bepi-Colombo during its Venus flyby, OSIRIS-REx after collection of a sample from Asteroid Bennu, Artemis I which was the uncrewed Moon-orbiting mission to test the SLS, and ESA's Mars Express orbiting Mars

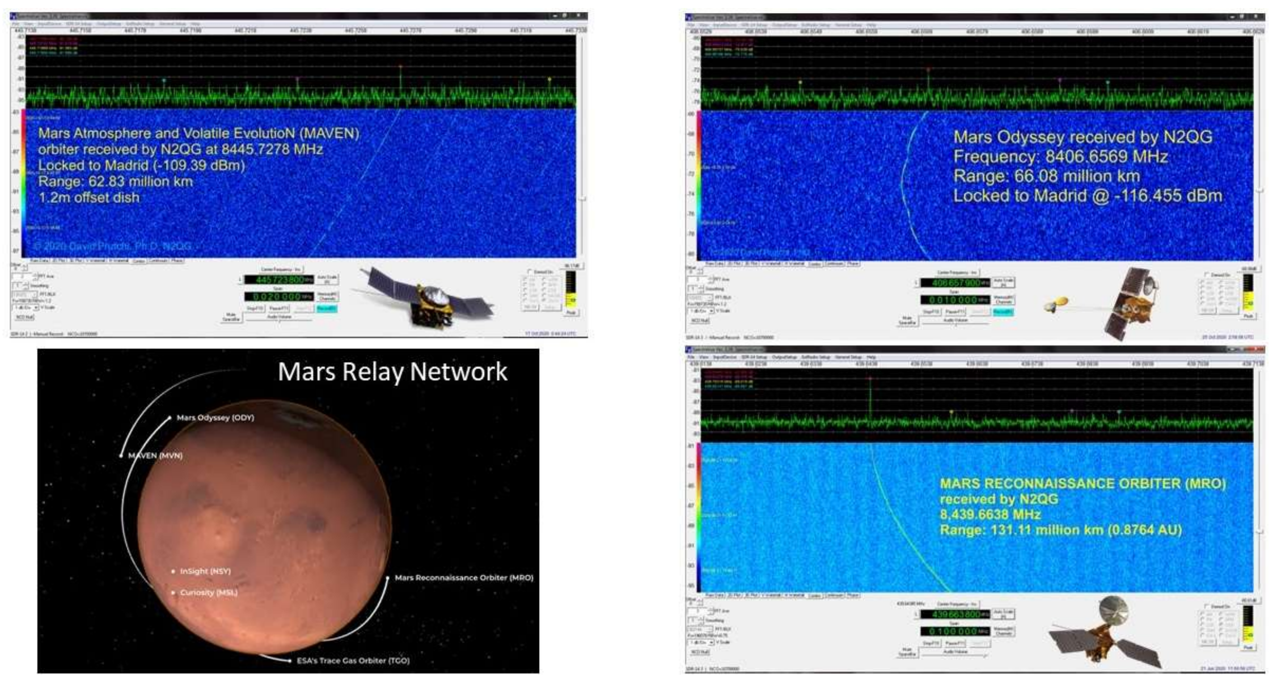


Figure 56 – It is not common for the landers and rovers to communicate directly with Earth. Instead, they communicate with one of the orbiters that acts as a relay to Earth. They do so in addition to their primary mission. The current relay network comprises Mars Odyssey launched in 2001, Mars Reconnaissance Orbiter (MRO) launched in 2005, MAVEN launched in 2013, and ESA's Trace Gas Orbiter launched in 2016.

In July 2020 three spacecraft were launched towards Mars. Given that we were isolating at home doe to COVID-19, this was a great opportunity to work on our systems and track the spacecraft from launch to their arrival to Mars.

Mars probes are not especially difficult to detect. Tianwen-1 is even easy to listen on speaker using the 1.2 m dish. I can't say the same about JUNO orbiting Jupiter, which took me a while to finally detect in 2021 when the spacecraft was at a distance of 616.46 million kilometers away from Earth (Figure 57).

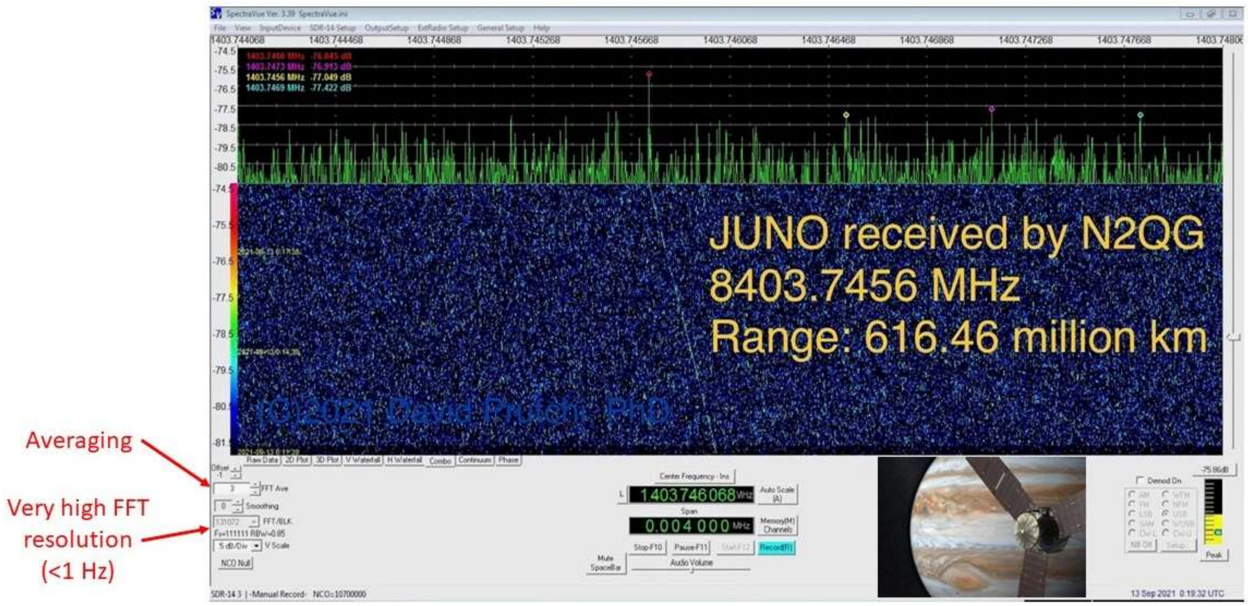


Figure 57 – My personal ODX so far is the JUNO Spacecraft orbiting Jupiter at a distance of 616.46 million kilometers from Earth.

This is by no means a record. As shown in Figure 58, Paul Marsh (M0EYT) has detected JUNO and Cassini when they were at 907.3 million and 1.37 billion kilometers away from Earth, respectively

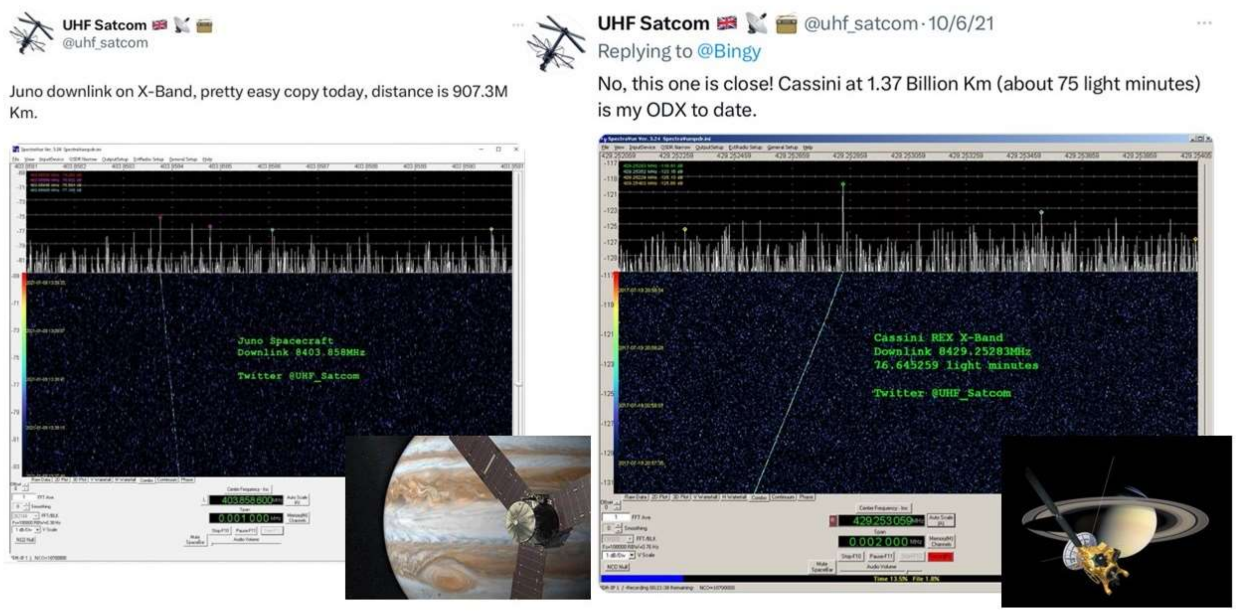


Figure 58 – Paul Marsh (M0EYT) has detected JUNO and Cassini when they were at 907.3 million and 1.37 billion kilometers away from Earth, respectively. Images used with permission, kind courtesy of Paul Marsh.

Daniel Estévez (EA4GPZ/M0HXM) holds the record Amateur DSN ODX with his detection of Voyager-1 at an astonishing 151.72 au (22.697 billion km away from Earth !!) using single 6m dish of the Allen Telescope Array. The estimated received power at antenna was barely -177.2 dBm. To achieve this feat, he integrated the spectra over 30 minutes using an FFT bin size of 500 mHz and Doppler-correcting with a resolution of ms. Daniel calculated that if he could continuously receive the signal with no drops he could detect signal with just 312.5 seconds integration.

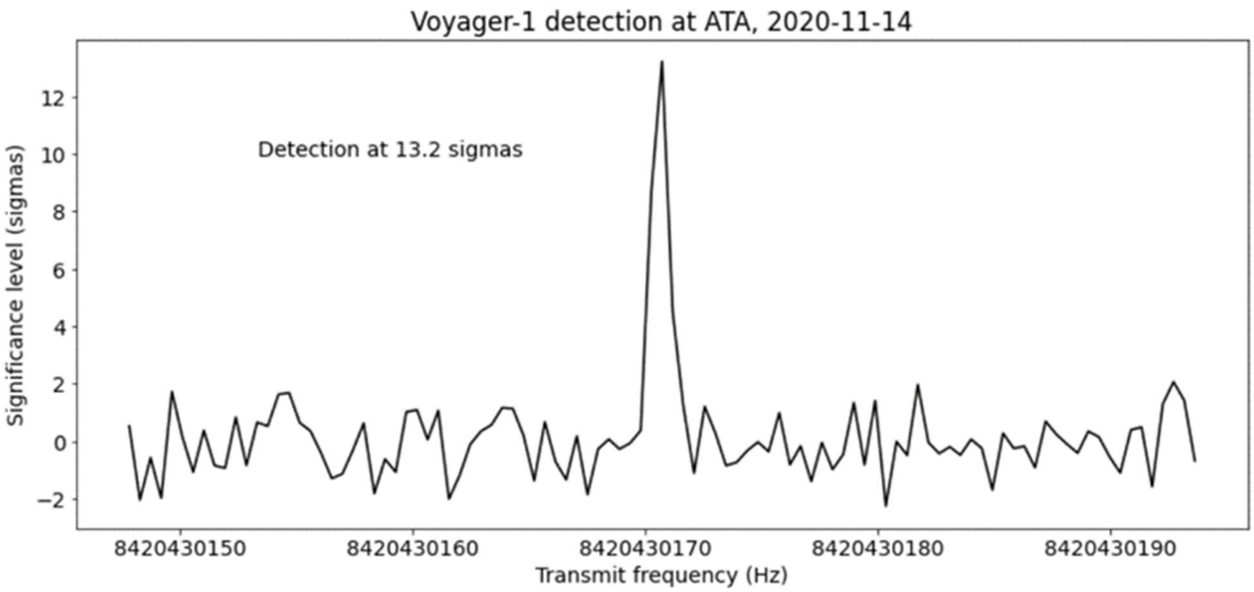


Figure 59 – The ultimate DX: Daniel Estévez (EA4GPZ/M0HXM) holds the record Amateur DSN ODX with his detection of Voyager-1 at an astonishing 151.72 au (22.697 billion km away from Earth !!) using single 6m dish of the Allen Telescope Array. Image used with permission, kind courtesy of Daniel Estévez.

16 Conclusion

Although to the naïve eye it may look like Amateur DSN is as fun as watching grass grow, it is actually a very challenging and rewarding activity. In fact, it is best suited for a ham or engineering school club activity because it requires expertise in so many disciplines. Additionally, the same equipment and techniques are suitable for radio astronomy, space communications, and moonbouncing.

Well, that's it for now. Hope this helps someone out there.

73,

David N2QG

17 RESOURCES

- #hearsat on Libera.Chat
- groups.io/g/Amateur-DSN

GURUS:

- Paul Marsh, M0EYT, uhf-satcom.com, 𝕏: uhf_satcom
- Scott Tilley, VE7TIL, skyriddles.wordpress.com, 𝕏: coastal8049
- Daniel Estévez, EA4GPZ / M0HXM, destevez.net, 𝕏: ea4gpz
- Joe Steinmetz, K6SAT, www.usa-satcom.com, 𝕏: usa_satcom
- Iban Cardona, EB3FRN, www.eb3frn.net, 𝕏: eb3frn
- Jakub Hruška, www.r00t.cz, 𝕏: @r00t

My projects:

- www.prutchi.com
- 𝕏: prutchi
- hackaday.io/Prutchi

YouTube:

- Iban Cardona (EB3FRN) in Spanish for the Unión de Radioaficionados Españoles: https://www.youtube.com/live/-EQTsaP-yoE?si=DAb9mw_HyID2LOg_
- Joe Steinmetz (K6SAT) for the Sierra Foothills ARC: https://youtu.be/gcYew7JhCLU?si=4ba8Zj0sYRu_UuVZ
- Paul Marsh (M0EYT) at the 2017 RSGB Convention: https://youtu.be/p5lGK4a_uv4?si=5KSk17cYT6Llf1ST
- Daniel Estévez (EA4GPZ / M0HXM) GNU Radio Tutorial at: https://www.youtube.com/@bsrctech

Software:

- PstRotator by Codrut Buda: https://www.qsl.net/yo3dmu/index_Page346.htm
- SpectraVue™ by RFSPACE: http://www.rfspace.com/RFSPACE/SpectraVue.html
- SatDump by Aang23: https://github.com/SatDump/SatDump
- satellite tracking toolkit for radio observations (RF) - STRF by Cees Bassa: https://github.com/cbassa/strf
- DragonOS: https://sourceforge.net/projects/dragonos-focal/