Amateur DSN Lessons Learned (so far…)

David Prutchi PhD, N2QG, October 15, 2020

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 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 the 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.

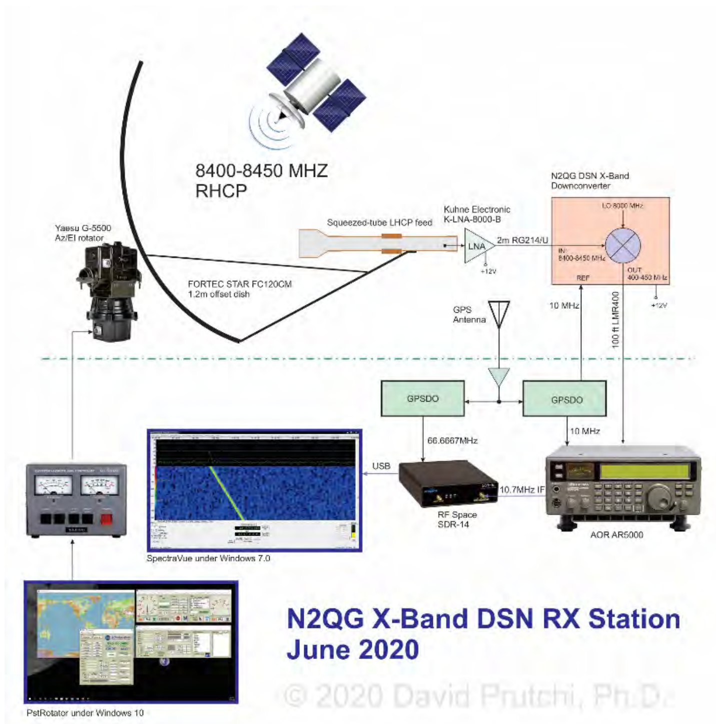

Figure 1 – Block diagram of N2QG's X-band Amateur DSN station in June 2020.

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.

Despite carefully tweaking the feed, I've been unable to get the system mounted on the 3.5m dish to yield the signal levels that I'm expecting. I suspect surface accuracy is the culprit because the 3.5m dish behaves

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well at 1296 MHz, but the g/t is just not there at 8.45 GHz. I can receive Bepi-Colombo on the 1.2m dish with around 12 dB compared to 16dB on the 3.5m dish. However, M0EYT receives it at around 30dB on his 2.4m prime dish. In July I worked on decreasing the SNR of the downconverter, which improved signals some, but definitely not as much as I would have liked to receive from a 3.5m dish.

Towards the end of that month I returned the X-band feed and downconverter to the 1.2m offset dish because I needed the 3.5m dish to participate in the EME SSTV Moon Landing Party hosted by PI9CAM at Dwingeloo Radio-Observatory in the Netherlands.

The Hope Emirates Mars Mission (EMM), Mars 2020 Perseverance, and Tianwen-1 launched right around that time, and I've been able to track them all with the 1.2m dish.

Juno remains out of my reach, so I'm considering next steps to improve my system. I thought that this would be a good point in time to summarize my experience so far, and discuss out loud plans for the future in case that it helps someone else who is just getting started in Amateur DSN.

1 Antenna (Reflector)

1.1 1.2m, f/d=0.6 offset dish (FORTEC STAR FC120CM)

Figure 2 – Fortec Star 1.2m, f/d=0.6 offset dish shown with S-, X-, and Ku-band feeds

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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 %

This is 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 2 shows some of the spacecraft and signal levels that I've received using this dish.

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

Spacecraft	Date/Time	Range (millions of km)	RX Frequency (MHz)	SNR (dB)	Comments
OSIRIS-ReX	September 13, 2020, 18:48 UTC	312.82	8445.5236	4	Locked to Goldstone - 120.750786 dBm
OSIRIS-ReX	October 10, 2020, 19:29 UTC	328.59	8445.742935	4	Locked to Goldstone -121.24 dBm. Received signal shown in Figure 3
STEREO-A	July 25, 2020, 17:21 UTC	180	8443.59755	10	downconverter v. 19Jul2020 with 20dB att in shack
Tianwen-1	July 31, 2020, 13:32 UTC	2.61	8430.91	22	
Mars 2020 Perseverance	July 31, 2020, 13:00 UTC	0.39	8414.8736	24	
Hope Emirates Mars Mission	July 22, 2020, 12:20 UTC	0.89	8402.6693	10	LHCP

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Spacecraft	Date/Time	Range (millions of km)	RX Frequency (MHz)	SNR (dB)	Comments
Mars Reconnaissance Orbiter (MRO)	October 15, 2020, 0:35 UTC	62.91	8439.3067	16	Mars in opposition. Prior lock to Madrid showed signal at -99 dBm

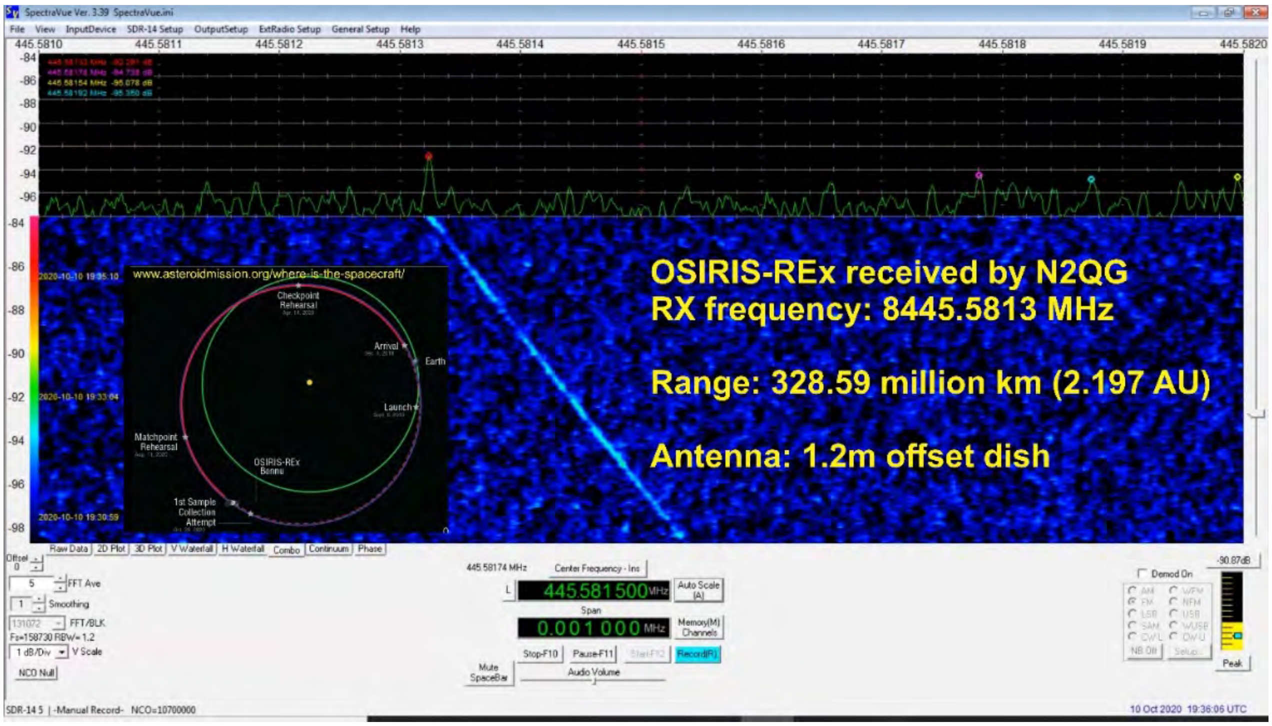

Figure 3 - OSIRIS-ReX received by N2QG at 8445.742935 MHz using 1.2m offset dish. Spacecraft was locked to NASA's Goldstone DSN, which reported a received power of -121.24 dBm

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. As shown in Table 2, signal levels are quite good for what I would expect from a small dish like this.

My main intention in setting up this dish was to use it as a testbed to figure out how to track DSN spacecraft, which was actually obviated by the introduction of the DSN feature in PstRotator. 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.

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1.2 3.5m (12ft) C/Ku-Band Prime Focus Mesh Satellite Dish (Tek2000.com)

Figure 4 – 3.5m mesh dish with X-band feed and N2QG downconverter mounted on the feed-point bracket.

The 3.5m dish is sold by Tek2000.com 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 5 and Figure 6).

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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/Time	Range (millions of km)	RX Frequency (MHz)	SNR (dB)	Comments
OSIRIS-Rex	June 21, 2020, 19:08 UTC	249.88	8445.5386	8	
Mars Reconnaissance Orbiter (MRO)	June 21, 2020, 11:49 UTC	131.11	8439.6638	8	Locked to Goldstone. Received signal shown in Figure 5
STEREO-A	July 4, 2020, 0:29 UTC	182.05	8443.57828	12	
Mars Express	June 12, 2020, 14:05 UTC	137.66	8420.6963	6	Received signal shown in Figure 6

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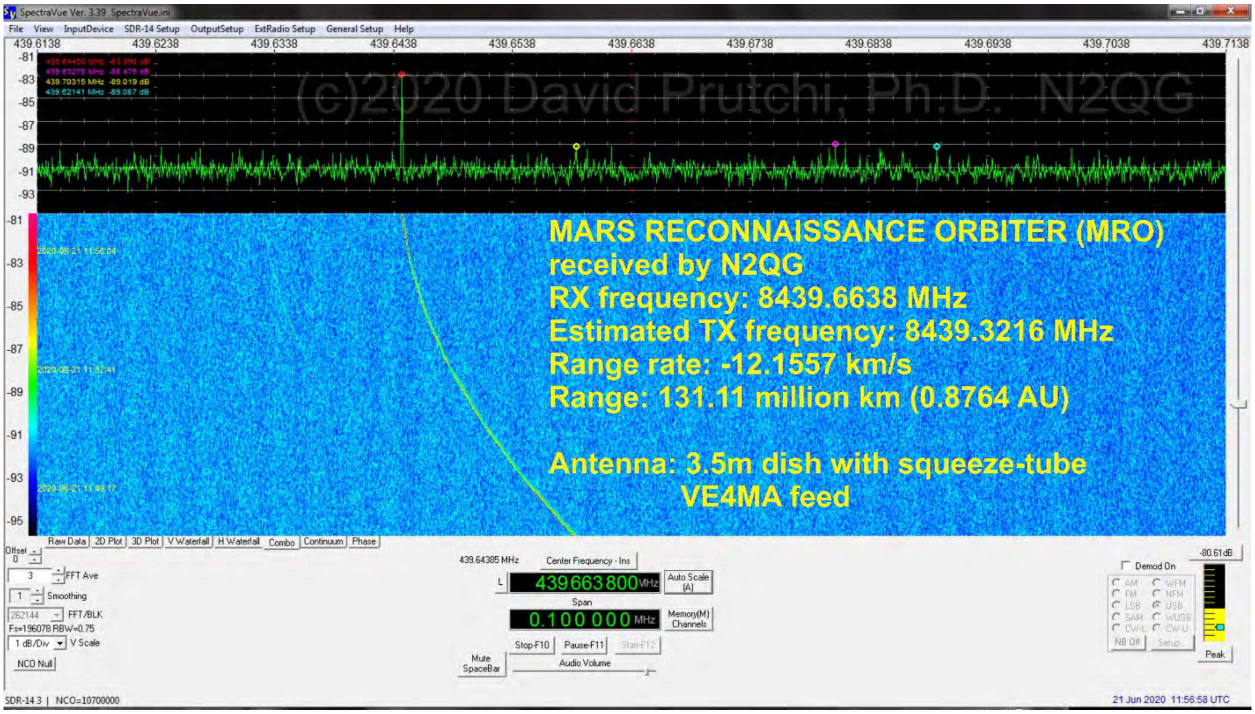

Figure 5 – MRO received by N2QG at 8439.66 MHz using 3.5m dish

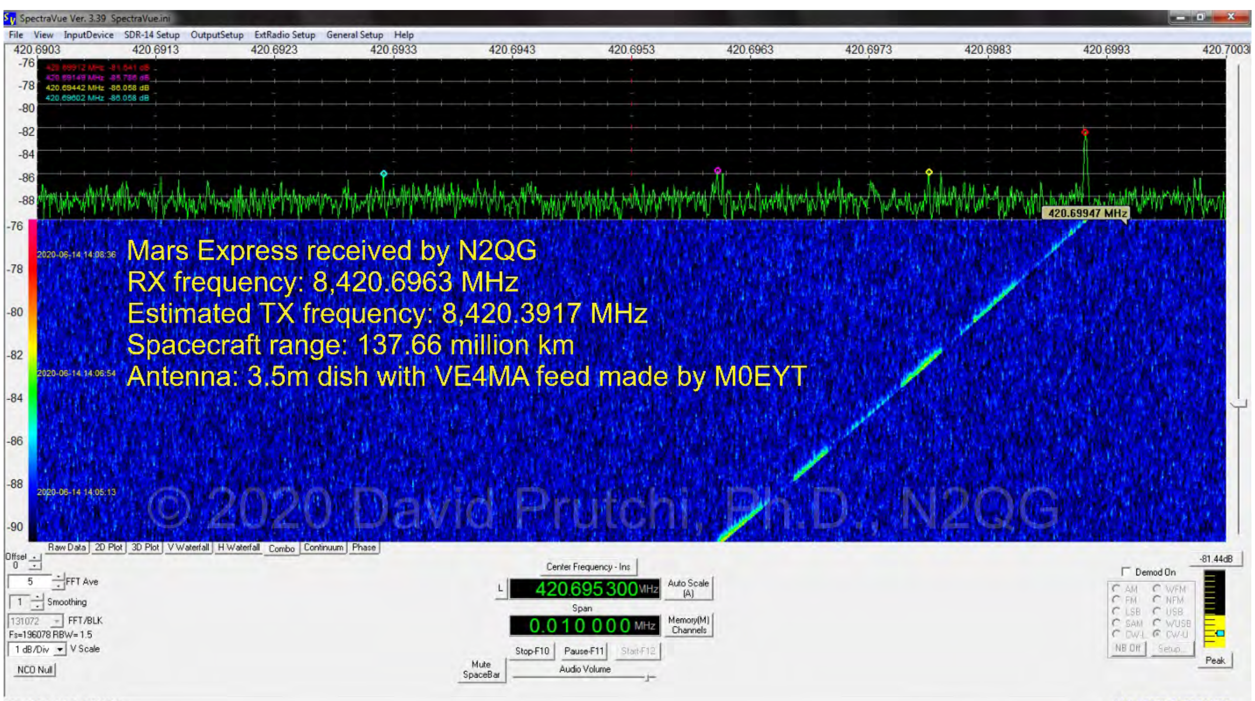

Figure 6 - Mars Express received by N2QG at 8420.6963 MHz using 3.5m dish

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This dish performs superbly at 1296 MHz, and I've used it to make many challenging EME contacts, including SSTV! It was thus rather disappointing to see that signal strengths from DSN spacecraft do not match 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 7 – 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 7, 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.

1.3 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 antenna system is the current limiting factor preventing me to observe the Juno spacecraft orbiting Jupiter. In addition, I do want to improve my signal to be able to demodulate and decode spacecraft telemetry.

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I'm thinking how to move forward in the next few months. 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.

2 Az/El Rotator and Controller

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

2.1 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.

2.2 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 an EME 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. I've had no need at all to recalibrate since I first installed it.

2.3 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

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3 Feed

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 8).

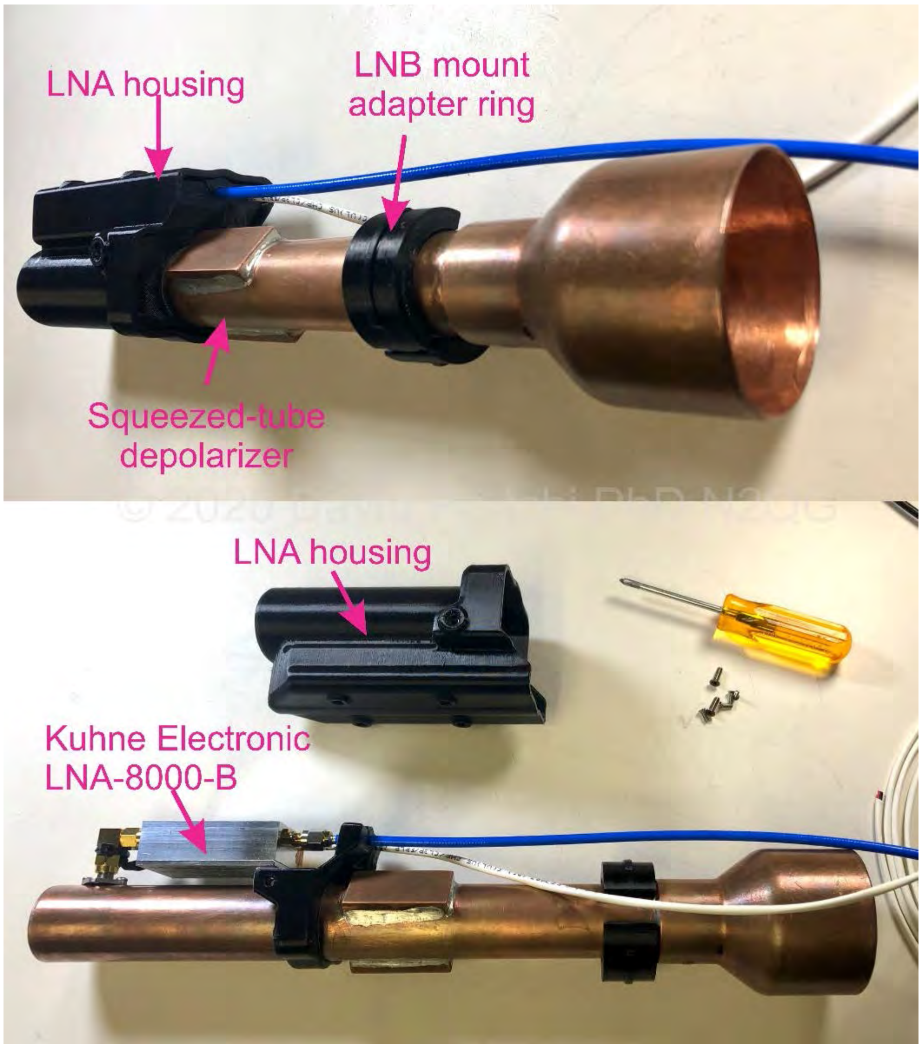

Figure 8 – 8.45GHz squeezed-tube feed built by KC2TDS based on SQ5KTM’s feed

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 scalar ring (Figure 9, 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.

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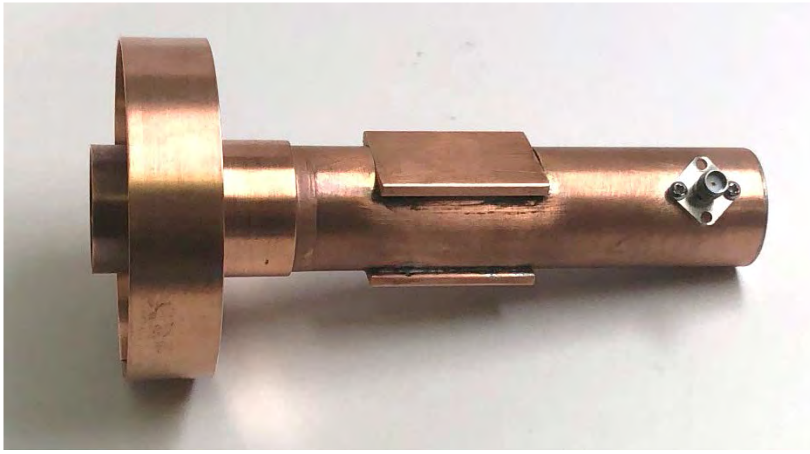

Figure 9 - Squeezed-tube depolarizer and super Kumar scalar ring built by M0EYT

Later, in preparation of the EMM launch, KC2TDS added a RHCP port to be able to receive the spacecraft's LHCP transmissions. The dual-port feed is shown in Figure 10.

Figure 10 – Squeeze-tube depolarizer feed built by M0EYT. RHCP and LHCP probes added by KC2TDS.

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3.1 Feed – Lessons Learned

The squeezed-tube depolarizer and super Kumar scalar ring is definitely the way to go. If built right, the quality of polarization is excellent, so I feel that adding a coupler is unnecessary. I intend to keep on using the unit built by M0EYT.

4 LNA

I use the Kuhne KU LNA 8000 B Super Low Noise Amplifier (Figure 11). This is a professional-grade amplifier with extremely low noise (Table 5), designed specifically for DSN reception.

Figure 11 - Kuhne KU LNA 8000 B Super Low Noise Amplifier. Image credit: Kuhne Electronic

Table 5 – 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 aluminium
Dimensions (mm)	50 x 30 x 17
Weight	45 g (typ.)

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4.1 LNA – Lessons Learned

I'm extremely satisfied with the performance of the Kuhne KU LNA 8000 B Super Low Noise Amplifier. It is difficult to imagine beating the performance of this LNA with a home-made unit, so I don't think that I'll be looking for alternatives. In fact, I would like to add a second unit so that I can switch between LHCP and RHCP without having to physically move the LNA between the ports of my feed. By way of explanation of why not use a relay before the LNA, relays add an enormous amount of noise (in fact, even coax adapters do), so the LNA really needs to be connected directly to the feed's probe.

5 Downconverter

Unfortunately, Kuhne Electronics no longer manufactures an 8.4Ghz LNC for DSN Rx (KU LNC 8084 A, RF in: 8000-8450 MHz, IF: 850-1300 MHz, NF: 1.2 dB, Gain: 25 dB), so I had to build my own downconverter. The specs of the KU LNC 8084 A are nevertheless interesting to use as a benchmark and are shown in Figure 12.

Deep Space Communications
KU LNC 8084 A - KU LNC 8084 A PRO

- Converter for receiving space probes
- Super low noise figure due to the use of the latest HEMT FETs
- Remote power supply via the coaxial cable
- Additional low noise amplifier available: KU LNA 8000 A

Specifications

Type	KU LNC 8084 A	KU LNC 8084 A PRO
Frequency range RF	8420 MHz	8420 MHz
Frequency range IF	1270 MHz	1270 MHz
Bandwidth	typ. 300 MHz	typ. 300 MHz
Local Oscillator (LO)	7150 MHz	7150 MHz
Noise figure @ 18 °C	typ. 1,2 dB, max. 1,4 dB	typ. 1,2 dB, max. 1,4 dB
Gain	typ. 30 dB, min. 25 dB	typ. 30 dB, min. 25 dB
Supply voltage	+12 ... 14 V	+12 ... 14 V
Current consumption	typ. 220 mA	typ. 220 mA
Input connector	SMA-female / 50 ohms	SMA-female / 50 ohms
Output connector	N-female / 50 ohms	N-female / 50 ohms
Case	German Silver	milled aluminium
Dimensions (mm)	74 x 56 x 30	82 x 64 x 22

Figure 12 – Specifications of the Kuhne LNC 8084A downconverter from the Kuhne Electronic Amateur Radio Products 2008 catalog

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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 13.

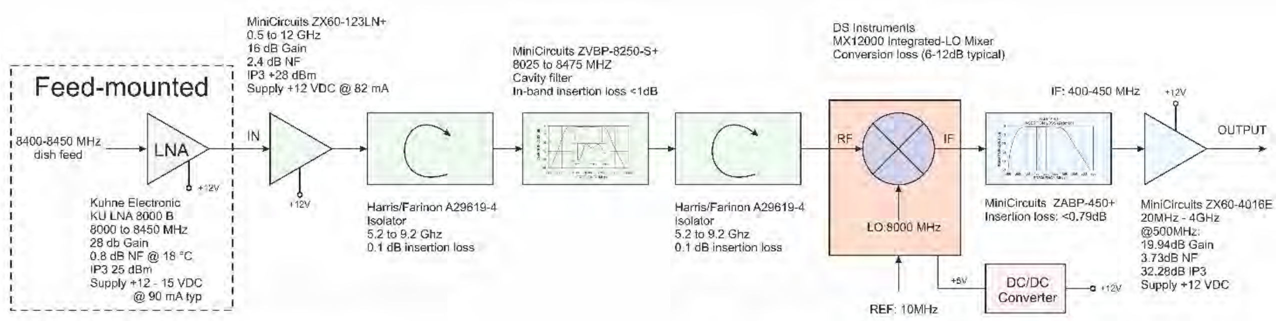

Figure 13 – Block diagram of the initial version of my downconverter.

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+ 8025 to 8475 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 current configuration is shown in Figure 14. As shown in Figure 15, 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.

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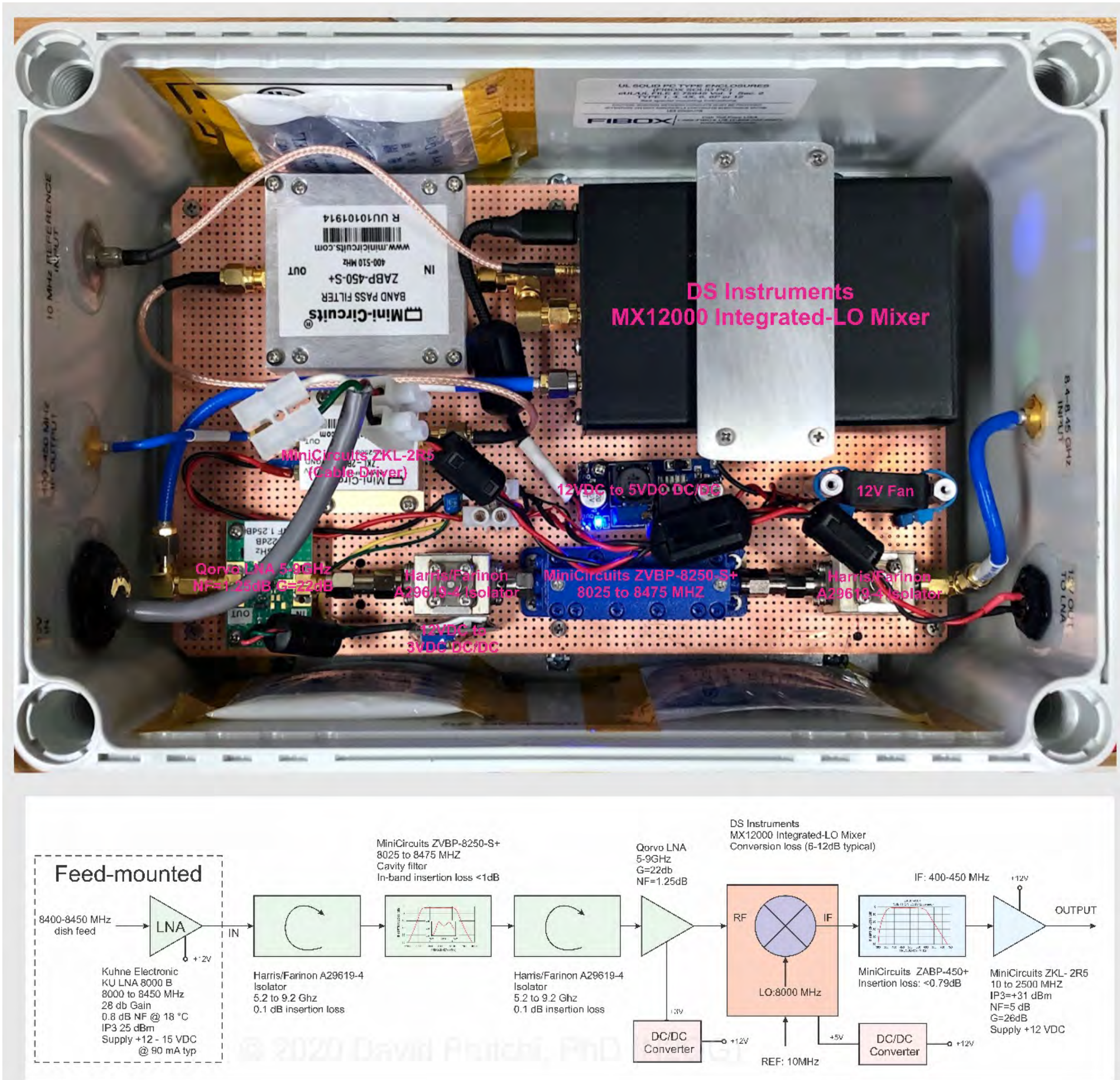

Figure 14 – Block diagram of my current X-Band DSN downconverter (last modified July 2020)

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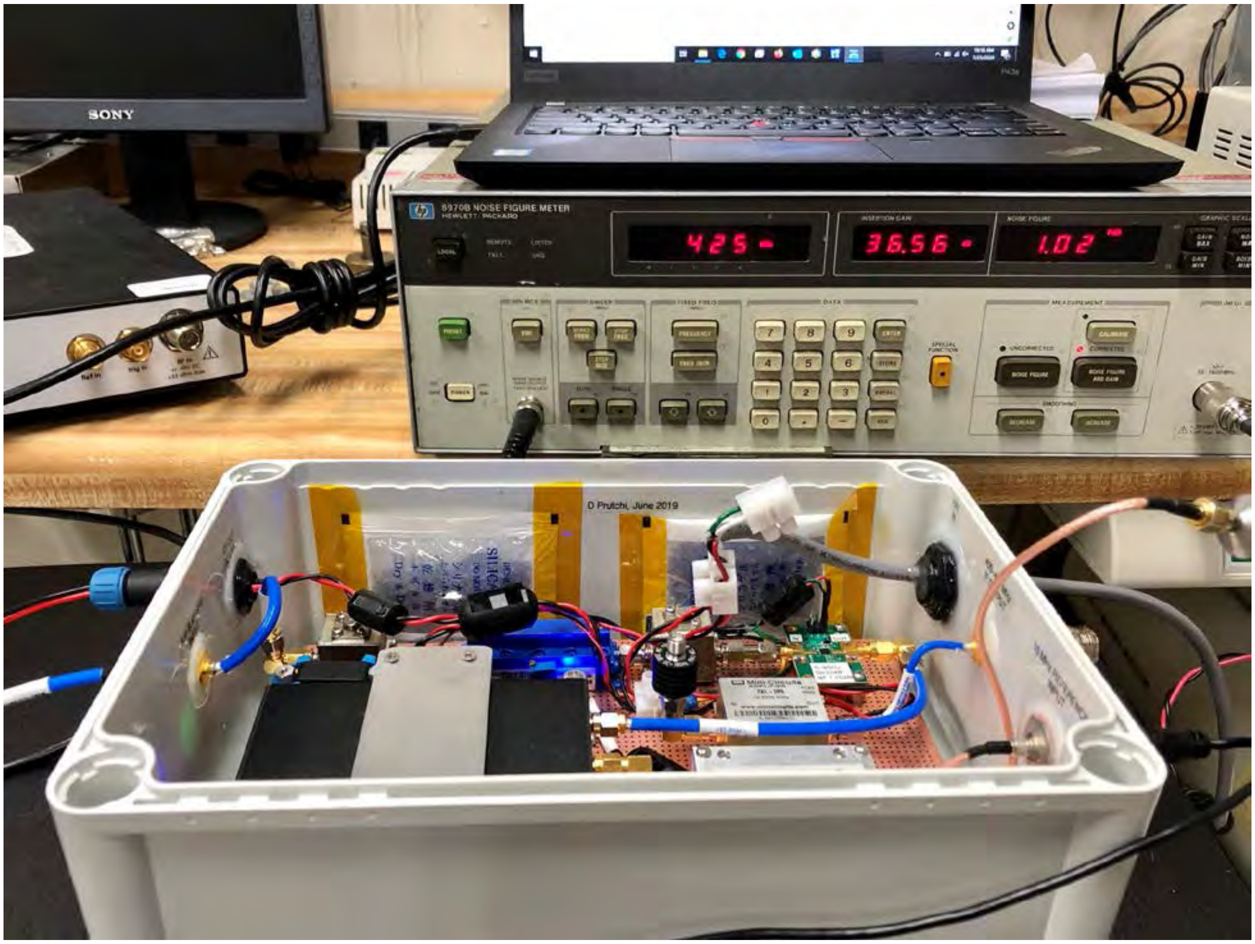

Figure 15 – Measurement of NF and gain of July 2020 version of the N2QG downconverter. Measurements are all the way from the input of the LNA to the output of the downconverter.

5.1 LNA – Lessons Learned

I'm very satisfied with the performance of my downconverter. My intention is to add 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.

6 Receiver and IF SDR

The receiver in my shack is an AOR AR-5000 (Figure 16). I LOVE this radio, and so do many of the 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.

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 7 (it doesn't like Windows 10) to control both the SDR-14 and the AR-5000.

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Figure 16 – My AOR AR-5000 receiver and the RFspace SDR-14 that I use for IF sampling.

6.1 LNA – 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 Unix. For this reason, I've been thinking about adding an Ettus USRP to my shack.

7 Software

7.1 Tracking

When I just started working on DSN, ephemerides 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 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.

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 on the 3.5m dish.

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7.2 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.

7.3 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. VE7TIL recently started using STRF to track and analyze Tianwen-1's flight to Mars.

The other area in which I'm interested is in demodulating and decoding these signals. EA4GPZ recently ran a GNURadio workshop exactly on this topic.

These new software tools mean that I will need to set up a separate Linux computer to run GNUradio and STRF, and get proficient with both. I'll also need a good refresher on orbital dynamics.

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

73,

David N2QG

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