THE SUM OF THE PARTS: Lessons learnt from designing and building a 3.7m S/X-Band antenna

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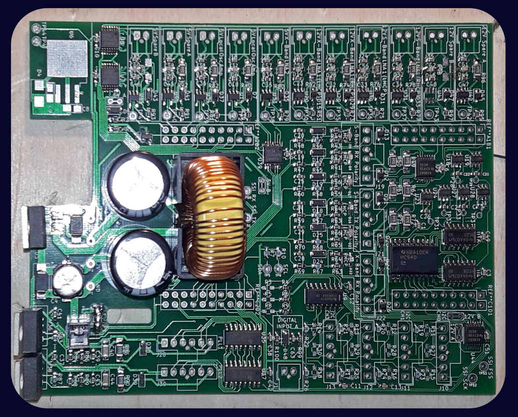
A redundant 2.2m Cossor weather radar was made available to us. After some initial experimentation tracking NOAA weather satellites, we challenged ourselves to convert it into a reliable high performance S/X-Band Station suitable for supporting LEO missions. A new reflector, horn feed, RF chain, motors and gearing were specified, designed and installed during the upgrade. Modern control software was written to command the new antenna.

We found that designing and assembling such a system is educational at a both a systems and component level. In particular, at X-Band we found there is little margin for errors where many small details, such as keyholing, pointing accuracy, feedback, gearing and RF chain considerations require careful engineering to give reliable performance.

Refurbishing the positioner

Assembling a new feed horn



Creating a new control board

KEYHOLING

Elevation over azimuth positioners are prone to the keyhole effect, where azimuth slew rate limitations of the antenna mount causes loss of tracking while the spacecraft is overhead. We needed to understand this problem in order to dimension our motors and gears. Such knowledge would contribute to our model describing the antenna's performance.

At low elevations the pointing error is proportional to the azimuth error; however, when the antenna approaches 90° elevation the azimuth error has no effect on pointing error. In practice the pointing error is tolerable provided the spacecraft remains within the -3 dB beamwidth of the antenna. Consequently, there exists a critical azimuth slew rate that the antenna must exceed to avoid keyholing at each pass elevation and antenna beamwidth.

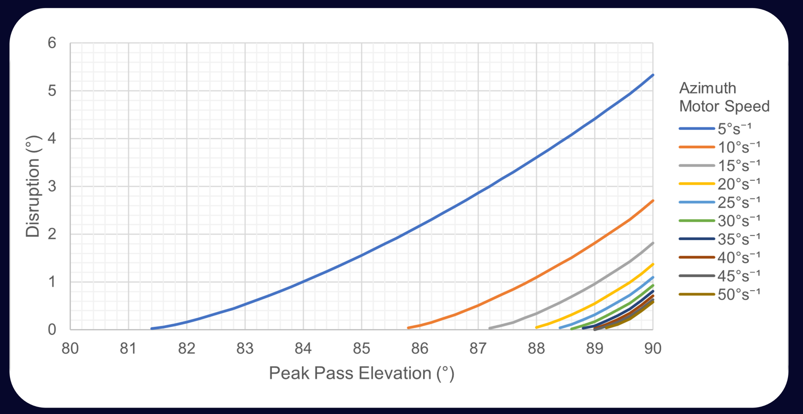


Figure 1. *Maximum antenna pointing error arising from keyholing at different pass altitudes. Different azimuth motor speed curves are shown to illustrate the sensitivity of motor speed on the magnitude of keyholing.*

Figure 1 shows for different antenna azimuth motor speeds, the characteristic curve describing the maximum disruption in degrees experienced depending on the pass' peak elevation. Analysing the magnitude of the disruption against motor speed indicates whether keyholing will occur for a given antenna beamwidth.

For a random orbit (assuming the spacecraft orbit hasn't been designed to pass over at a particular elevation) there is a higher probability of lower elevation passes than higher elevation passes. The probability of experiencing keyholing is thus not linearly related to the elevation where keyholing occurs.

The total disruption time due to keyholing is dependent on the maximum azimuth slew rate of the antenna as shown in Figure 2. We found the recovery time is shortest if the keyholing is symmetrical. To achieve symmetrical keyholing the antenna must accelerate to maximum speed sufficiently early so at the peak elevation the azimuth is passing its correct value.

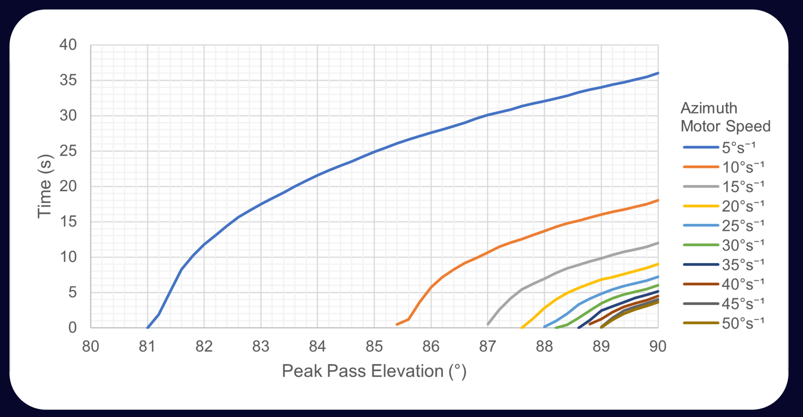


Figure 2. *The amount of time the antenna needs to catch up with the spacecraft arising from keyholing at different pass altitudes. Different azimuth motor speed curves are shown to illustrate the sensitivity of motor speed on the time duration of keyholing.*

POINTING ACCURACY

Tracking the sun provides a practical technique for determining the absolute accuracy of a system at S & X-Band as well as measuring the G/T of the system using the Y-factor technique. However, a sun-track contains limitations:

- The large diameter of the sun means the antenna beamwidth will appear wider than it is. Therefore, it is critical to measure antenna performance using -3dB points to get accurate results
- At higher latitudes, the sun rises low on the horizon during winter. When it is not possible to track the sun, the moon can be tracked at X-Band as it rises to a similar height all year, although it radiates a weaker signal.
- The sun travels relatively slowly across the sky, so it cannot characterise the dynamic pointing accuracy of an antenna.

To characterise the dynamic pointing accuracy of an antenna it is necessary to observe moving targets.

For convenience we chose the NASA Aqua satellite for our analysis. Over a period of weeks the signal strength was recorded automatically throughout every pass.

We built a model to normalise the received signal, taking into account the distance to spacecraft and the spacecraft's antenna pattern, and compared it to the actual signal strength measured. We used this to validate the system's performance, as shown in Figure 3.

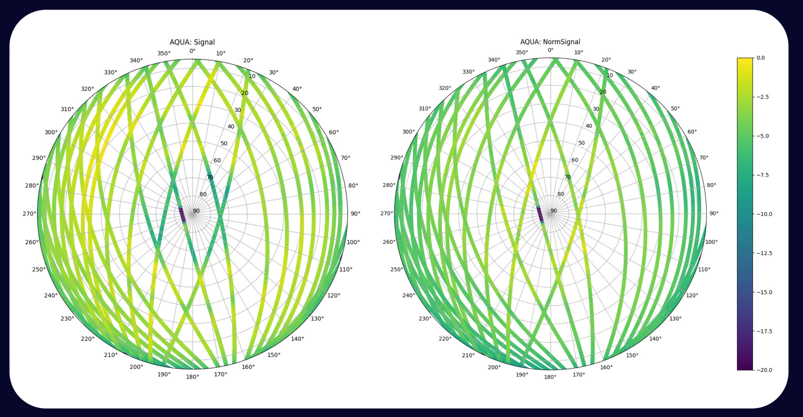


Figure 3. *Relative received signal strengths for 37 Aqua satellite passes showing (left) received values, (right) normalised values adjusted for range and spacecraft antenna pattern.*

ANTENNA CONTROL UNIT

The antenna control unit (ACU) is a critical component in the antenna assembly. It needs to calculate the spacecraft orbit and drive the motors and antenna subsystems accordingly. At high elevations, when the azimuth rate and elevation rate are high, any timing offset in the ACU causes pointing errors. Our design used COTS components and we abandoned adapting freeware software, preferring to code our own implementations in Python.

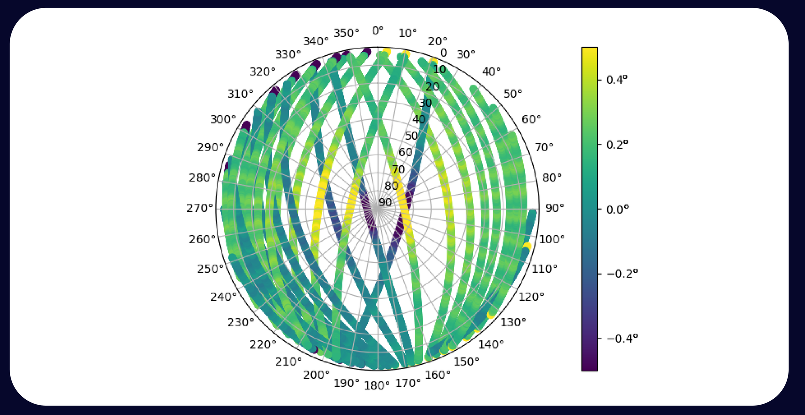


Figure 4. *Azimuth-elevation diagram showing the difference between the motor-based encoder and an existing antenna encoder gathered from the ACU metrics. A periodicity of 10° can be seen in azimuth.*

Metrics such as LNA and HPA currents, temperatures, fan speeds, signal levels and a secondary encoder system were found useful for validating the system. For example, by post-processing the metrics we were able to discover a secondary encoder was misaligned as shown in Figure 4.

Measuring component current draws provides a very fast, easy way to remotely monitor how well the system is functioning: motor current on the elevation axis is proportional to torque, which will be present if there is any imbalance in the counterweights. Current measurement of an LNA will confirm the LNA is turned on and the power connectors are firm as shown in Figure 5. Current ripple in an HPA fan will show the fan is spinning and not jammed.

Automation of pass scheduling and processing is critical, even for testing and university research projects because passes often occur at inconvenient times. Automation also frees up time for other aspects of the mission.

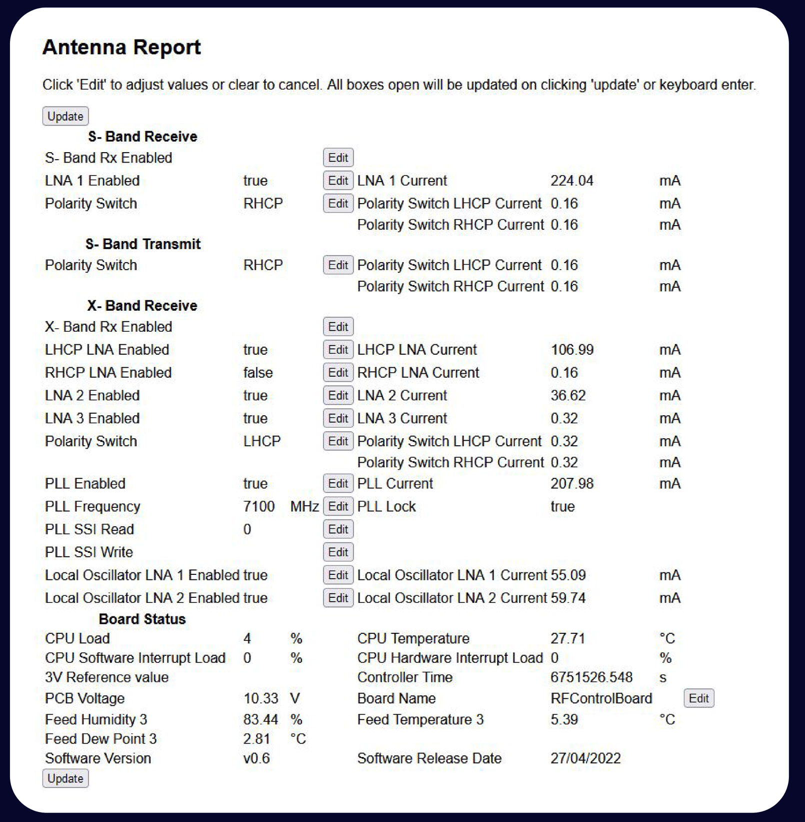


Figure 5. *The ACU's current measurement metrics confirm the LNAs are nominal.*

RF CHAIN

Receiver performance is limited by the antenna and front-end noise temperatures. Minimising the noise temperatures played an important part in our component selection and layout. High quality, reasonably priced LNAs are now readily available, although performance is always dependant on VSWR.

For X-Band, many missions require wide (up to 250 MHz) bandwidths, so maintaining adequate flatness across the bandwidth becomes significant because VSWR mismatch will cause passband ripple. Cavity filters have poor VSWR outside their passband and many mixers have very poor return losses, both of which can cause problems for the LNA. Careful placement of amplifiers and attenuators is required to absorb reflections caused by components with poor VSWRs. We found it necessary to correct the response across the IF bandwidth with a slope attenuator.

DISCUSSION

We built an antenna from new and repurposed components that operates with industry accepted performance. The challenge was not trivial; we found but it proved extraordinarily useful in determining the design constraints and parameters, and ways for finding engineering solutions. In essence we were able to build a system that was little different from the 1960s, but implemented with 2021 technology solutions assisted by digital processing facilitated by good access to numerical techniques and high performance modelling platforms. We are applying the knowledge we have gained to fabricate a second antenna which will have even better keyholing, tracking and RF performance.

FURTHER INFORMATION

For more information about this project, please contact:
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