Baseline ISS Comm Link Budget

What is a Link Budget?

A link budget is accounting of all of the gains and losses from the transmitter, through the medium (free space or cable) to the receiver in a telecommunication system.

It is similar to an accounting ledger or checkbook register in that it accounts for gains (income) and losses (expenditures).

Parts of the Communications Link

A link budget consists of the following sections which correspond to the segments of the communications link being analyzed:

- Transmitting system analysis
- Free space propagation analysis
- Receiving system analysis

There is some crossover between these parts when it comes to working the figures.

We will examine each in turn, working our way from ISS to the ground station receiver.

Scope of this Presentation & Videos

- We will focus upon a specific communications link budget; receiving ISS voice transmissions.
- There are normally at least two link budgets developed, one for uplink, and one for downlink.
- Since we only need the downlink, and other links only differentiate by the equipment used, bandwidth, and frequency, only a downlink link budget will be presented.
- The system to be analyzed will be simplified to illustrate the concepts without excessive detail.

Scenario Details

Transmit Segment Data

The transmitter is a 25W FM transceiver located in ISS tuned to 437MHz transmitting voice. The RF output of the transceiver is connected to 10ft of TCOM-400 cable and a bulkhead connector. No RF switches or in line filtering are installed. The transmitting antenna is a +6dB Yagi antenna pointed NADIR (directly downward). The antenna pattern is a typical yagi with a 120° cone at the -3dB gain rolloff point.

Free Space Propagation Segment Data

The altitude of ISS is assumed to be 400km above sea level (400km ASL). The ground station altitude is assumed to be at sea level (0km ASL). The elevation angle that the ground station observes ISS is 60° above the local horizon. The ground station observation is at night (no solar noise) and it is not pointed at any astronomical noise sources. The weather is clear with normal air pressure and humidity. A heavy industrial area is located within 50km of the ground station, providing 1200K of noise temperature.

Receive Segment Data

The receiving antenna is a +4.6dB quarter wave ground plane antenna pointed at zenith (directly upward). The antenna pattern is a typical for the type with a half torus extending from 15° above the horizon to a 30° cone at the -3dB gain rolloff point at the top (top blind). The antenna is connected to 10ft of LMR-400 cable which goes into a Realtek RTL2832 SDR dongle with an R820T tuner chip. No RF switches, in line filters, or low noise amplifiers are installed.

Transmitting Segment

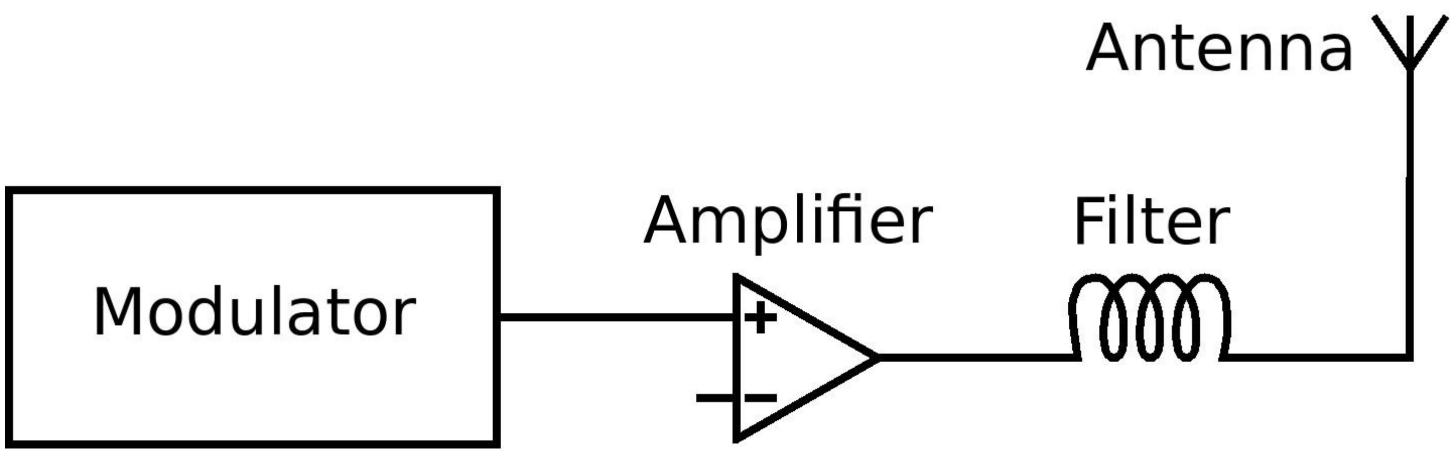
Transmitting System Components

Components of a typical transmitting system include:

- Modulator
- Power amplifier
- Transmission lines and connectors
- Output filters and in line switches
- Antenna

Corresponding data points of interest include:

- Modulation type and bandwidth (used later)
- Amplifier output power
- Transmission line and connector losses
- Output filter and switch losses
- Antenna gain, pattern and polarity (used later)



Transmitting System Analysis

In our scenario, ISS crew is using a 25W FM transceiver on 437MHz transmitting voice. The RF output of the transceiver is connected to 10ft of TCOM-400 cable and a bulkhead connector. No RF switches or in line filtering are installed.

The transmitting antenna is a +6dB Yagi antenna pointed NADIR (directly downward) with a typical yagi pattern; a 120° cone at the -3dB gain rolloff point..

Conversion:

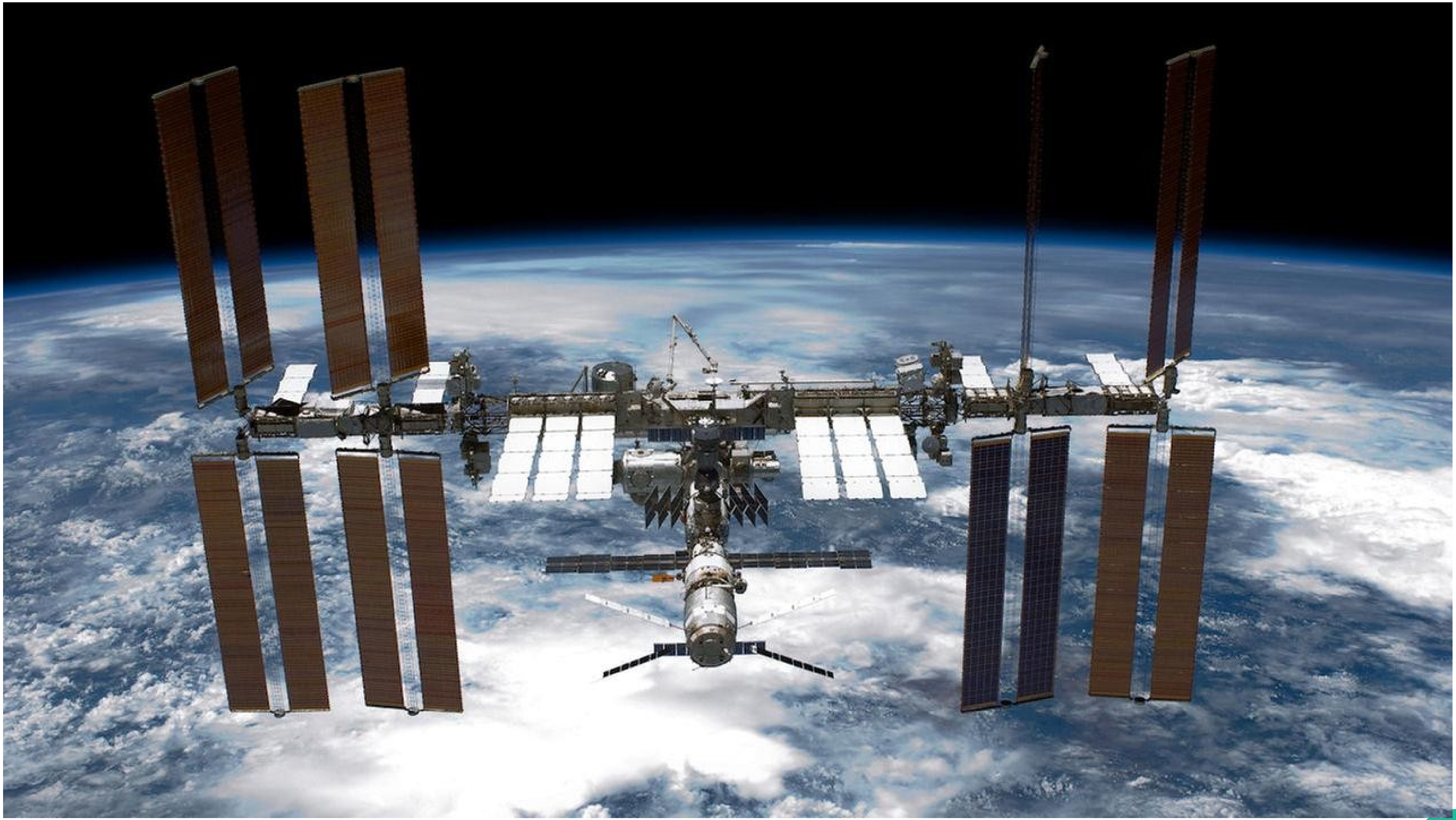
- **25 W = 14 dBW**
- **P(dBW) = $10\log_{10}(P(W)/1W)$**
- **P(W) = 1W · 10(P(dBW)/10)**

Assumptons:

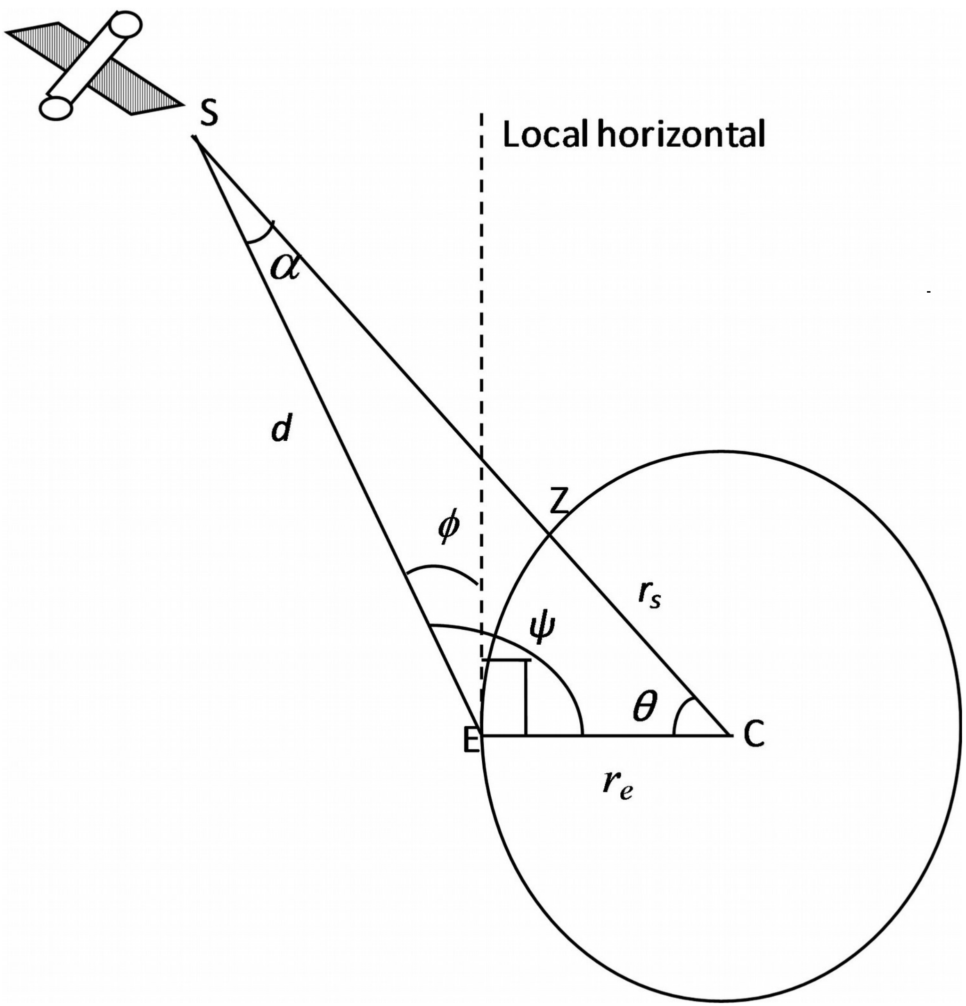
- **-1.2 dB loss on 10ft of TCOM-400 transmission line**
- **-0.5 dB loss on the four connectors (radio, bulkhead, bulkhead, antenna)**
- **-3 dB pointing loss (determined by antenna pattern)**

RF Output Power:	14 dBW
Connector Loss:	-0.5 dB
RF Line Loss:	-1.2 dB
Pointing Loss:	-3 dB
Antenna Gain:	+6 dB
Resultant Effective Isotropic Radiated Power (EIRP):	**15.3 dBW** **33.88 W**

Free Space Propagation Segment



Free Space Propagation Analysis



In the illustration on the left, we are primarily interested in the side of the triangle between ISS (S) and the ground station (E), designated (*d*). This is the slant range which determines how much of the signal we end up with at the ground station.

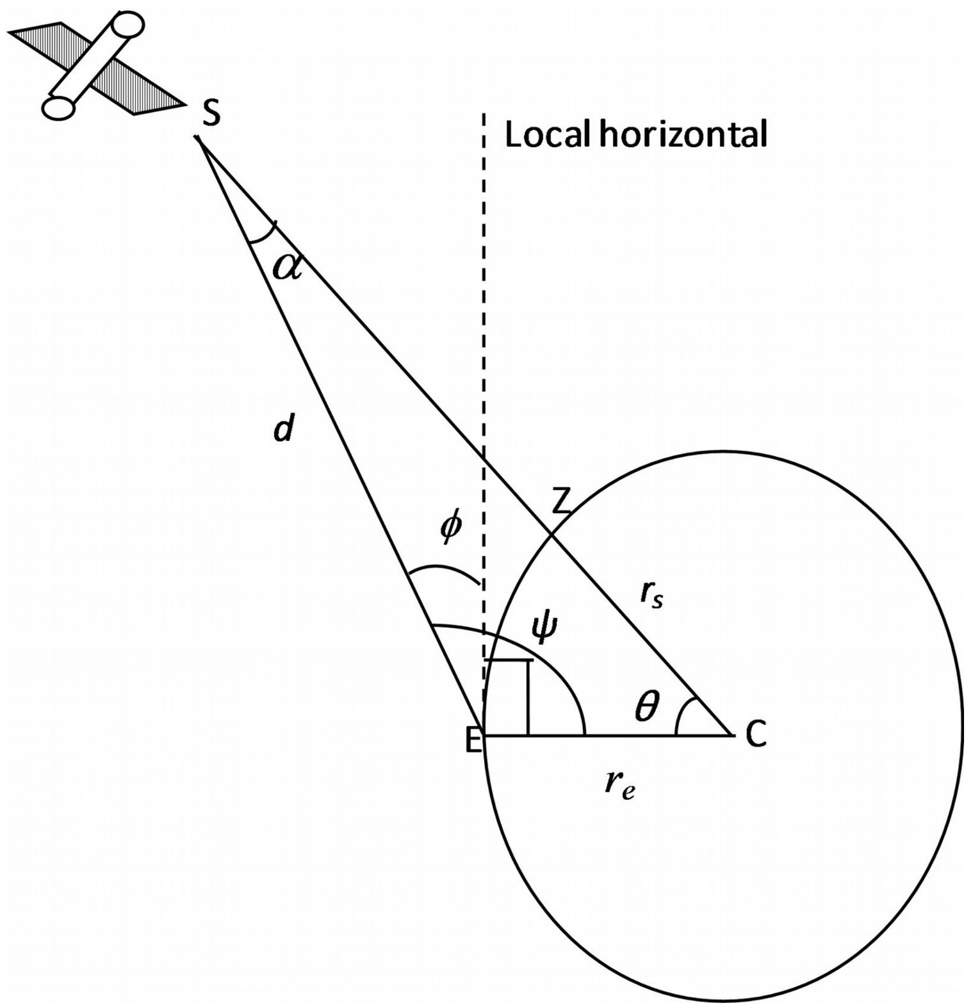
We know the altitude of ISS (*400km*), the radius of the earth (r_e*=6368km*), the altitude of the ground station (not shown since the scenario defines this as sea level), and the observation elevation above local horizontal (Φ*=60°*).

From this we can calculate the ISS orbit radius (Z): altitude + r_e = 6768km

We can also calculate the angle from earth's center to ISS, $\Psi = \Phi + 90^\circ = 150^\circ$

For the remainder of the equations we will need to resort to some trigonometry.

Free Space Propagation Analysis



The Law Of Sines dictates that the ratio of the sine of an angle over the length of the opposite segment is equal to both other ratios:

$$\frac{\sin(A)}{a}=\frac{\sin(B)}{b}=\frac{\sin(C)}{c}$$

Therefore, since we know the orbit radius (Z) and the ground station angle (E), we have one of the ratios:

$$\frac{\sin(\Psi)}{Z}$$

Since we know the radius of earth (r_e), we can compute the nadir angle (*α*) by applying the law of sines:

$$\frac{\sin(\alpha)}{R(e)}=\frac{\sin(\Psi)}{Z}$$

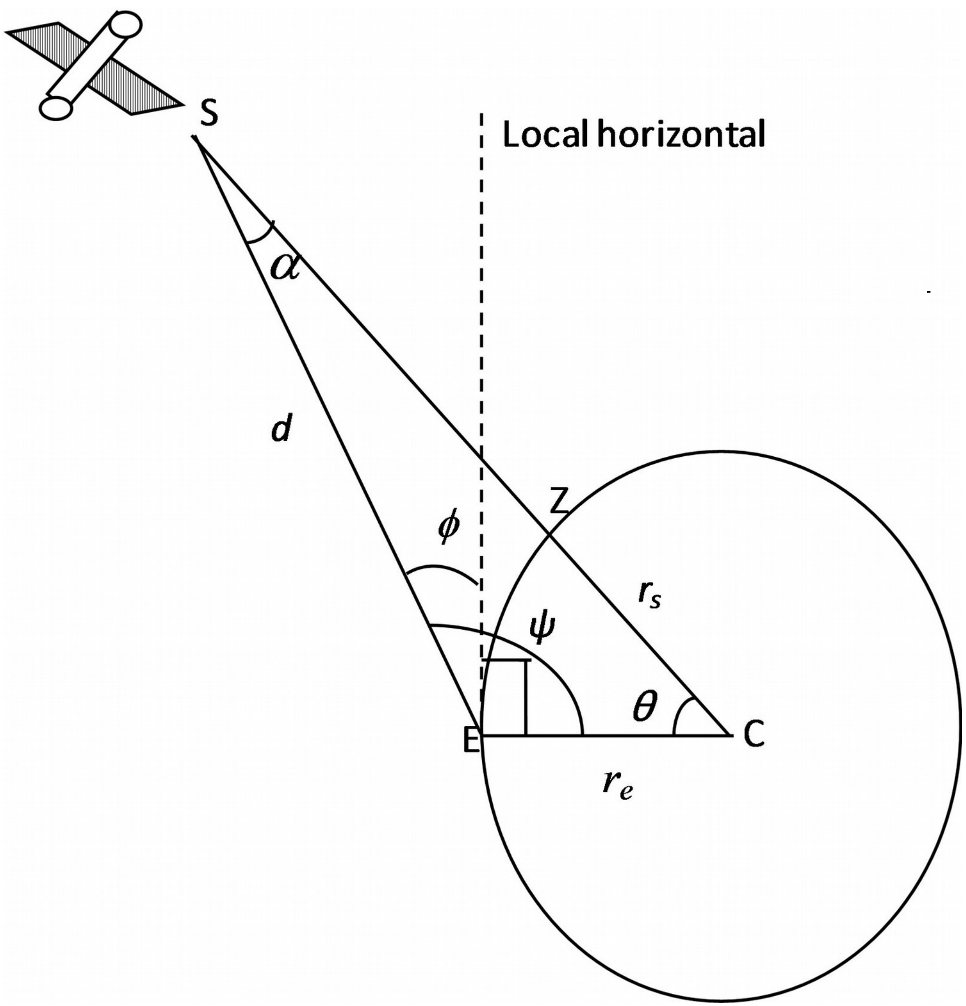
Substituting the known values: $\frac{\sin(\alpha)}{6378}=\frac{\sin(150)}{6778}$

Reduces to: $\sin(\alpha)=\frac{6378}{13556}$

$$\alpha=\sin^{-1}(0.4705)$$

The Nadir angle (*α*) = 28.066°

Free Space Propagation Analysis



We now know the value of angles *Ψ* (150˚) and *α* (22.066˚) and since the angles of a triangle must add up to 180˚, the central angle *θ=180-(Ψ+α)* or 1.934˚

Applying the law of sines again, we can solve for *d*:

$$\frac{\sin(\Theta)}{d} = \frac{0.5}{6778}$$

$$d = \frac{1}{\sin(1.934) * 13556}$$

Our slant range to ISS (*d*) is 457.42km

Free Space Propagation Analysis

Now that we know the distance between ISS and the ground station, we can use this to find out how much signal is lost in the space. This will represent the largest attenuation of our signal.

As illustrated on the right, energy travels away from the source, it spreads over a larger area, making the signal available at any point less, reduced by the square of the distance. The frequency of the signal also plays a part.

In the equation below, the 32.54 number is the adjustment factor allowing the use of km for the distance and MHz for the frequency:

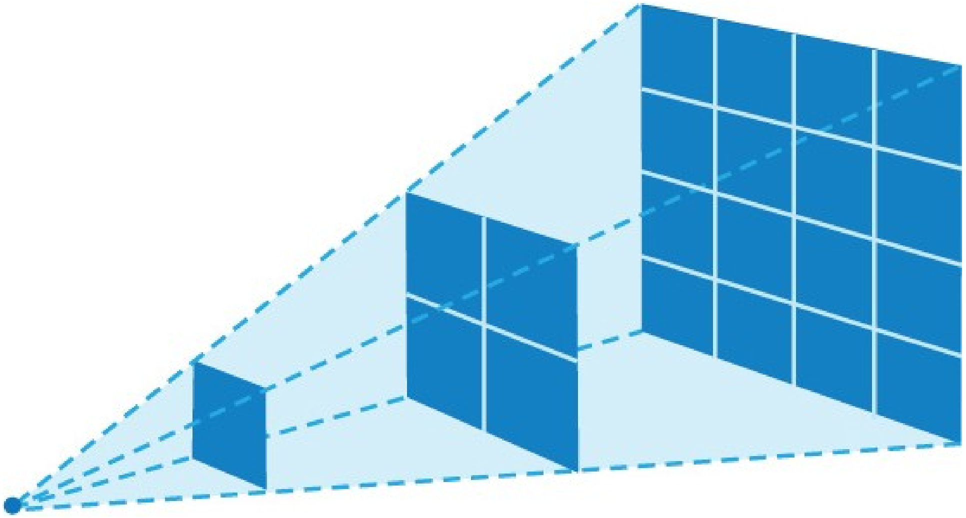
$20\log_{10}(d)+20\log_{10}(f)+32.45$

Substituting known values:

$L_s=20\log10(457.42)+20\log_{10}(437)+32.45$

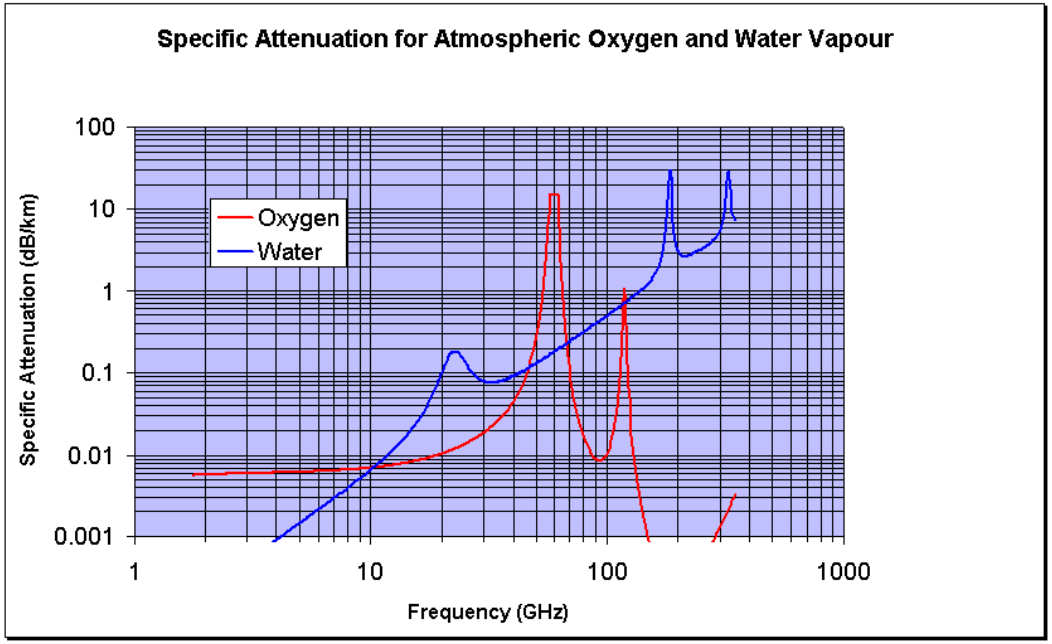
Our free space propagation loss (L_s) comes to -128.87 dB.

This means that our signal level which started out with an EIRP of 15.3dBW or 33.88W is down to a faint -113.57 dBW, which is well under a nanowatt.



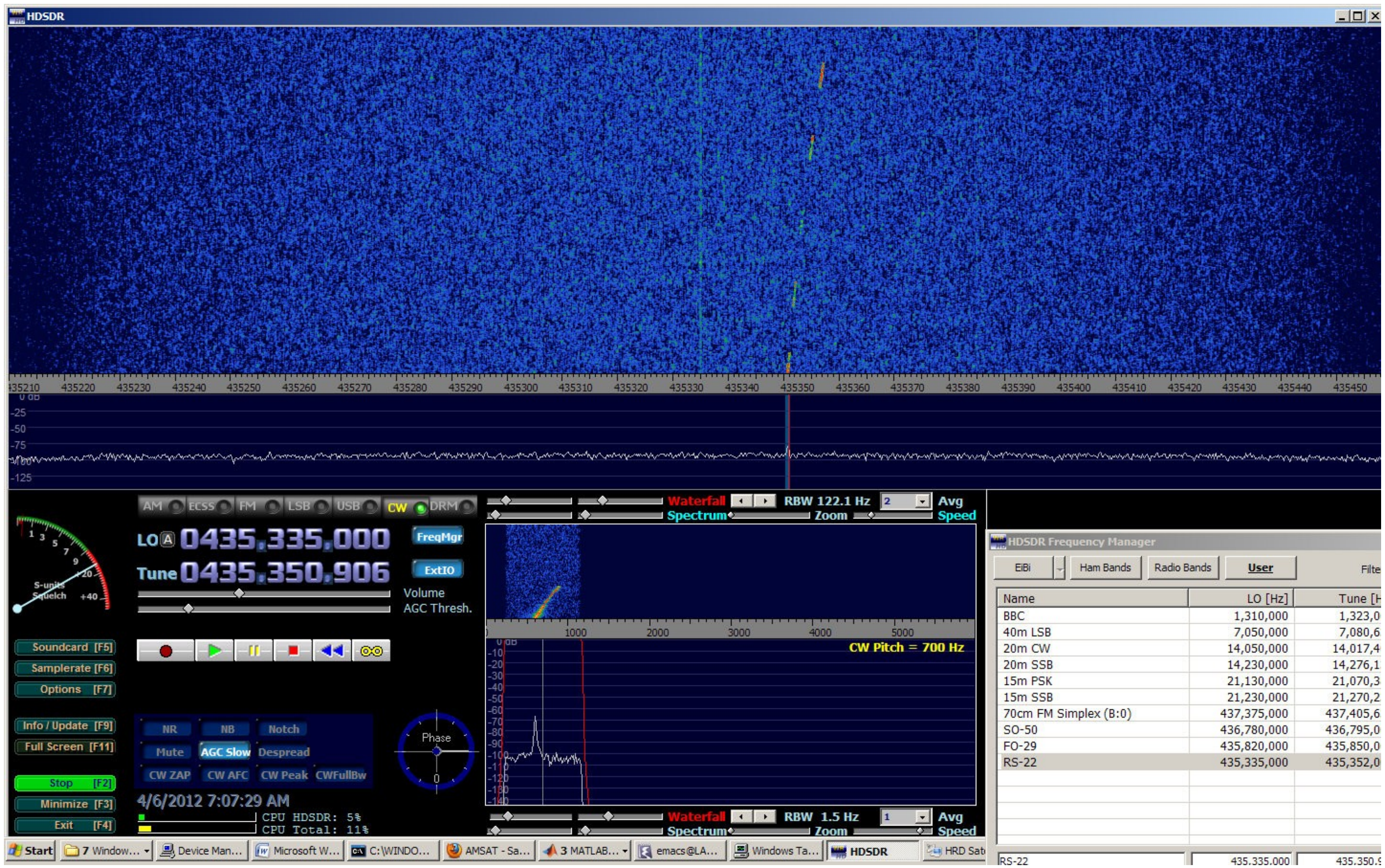
Atmospheric Losses

Absorption characteristics of atmospheric gases cause additional signal loss. As can be seen in the chart below, the oxygen in our atmosphere absorbs UHF frequencies at about 0.007dB/km.
With a slant range of 457km for a 400km altitude orbit, the karman line of 100km altitude occupies the lower quarter, or 114.25km of the slant range.
Atmospheric attenuation at 437MHz is 114.25 * -0.007 = -0.8db. Note that this will vary somewhat with weather conditions, especially at higher frequencies.
This brings our signal down a little more to -114.37 dBW.



Noise

Come On Feel the Noise



As if receiving this small signal wouldn't be difficult enough, noise from various sources can make it like finding a needle in a haystack. Fortunately, we have tools to see the signal such as the waterfall display above, but this only shows us the signal; it does not make the signal easier to receive. There is a satellite signal in the noise. It is the curved dashed line to the right of the center of the waterfall display.

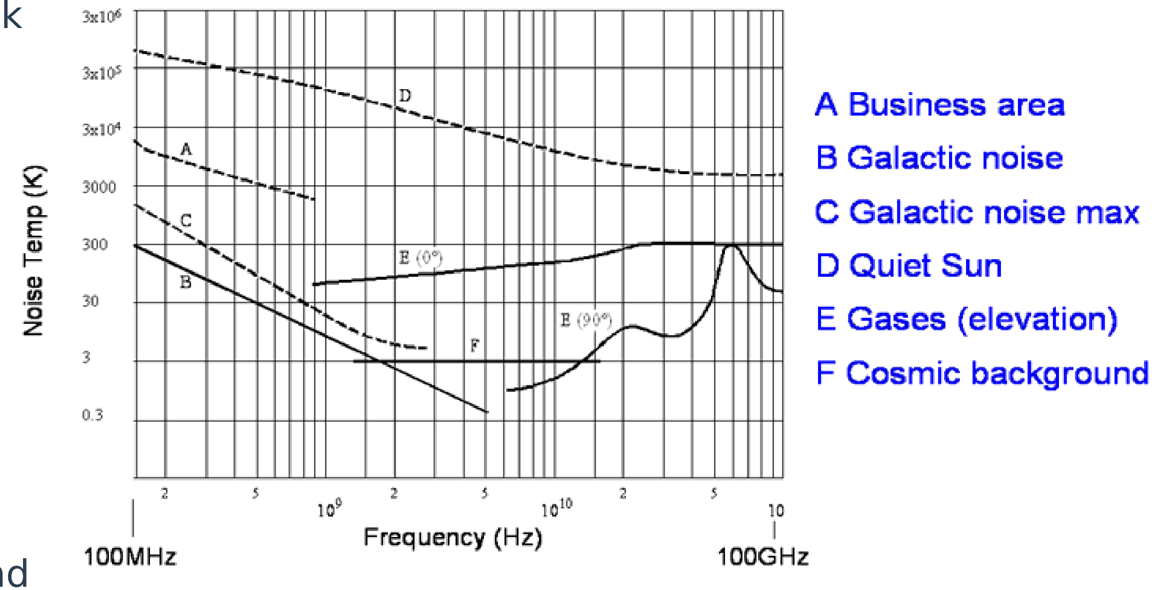
We need to understand the sources and nature of noise to bring in our signal.

Sources of Noise

There are many sources of noise which may interfere with our ability to bring in the weak signal. The following are sources with their anticipated noise temperature at 400MHz:

- Galactic sources (Vary from 10-250K)
- Cosmic background of (2K)
- The atmosphere (32K)
- The Sun (300,000K on a quiet day)
- The Earth (290K)
- Man made noise (varies from near 0 to 4,500K in industrial areas)
- Equipment noise (varies by equipment and ambient conditions)

Some noise sources we do not have to worry about. For example, the earth is a fairly strong source, but we will be pointing generally upward and separated by a ground plane. Some are best dealt with by avoiding them such as avoiding industrialized areas and not pointing the antenna at the sun.

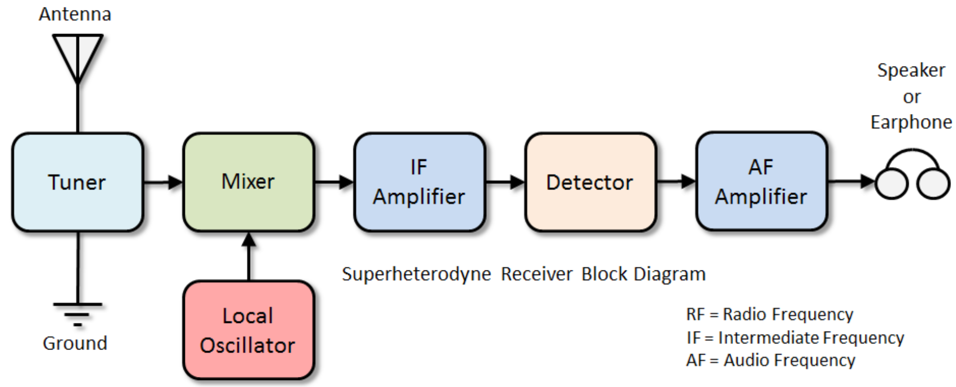


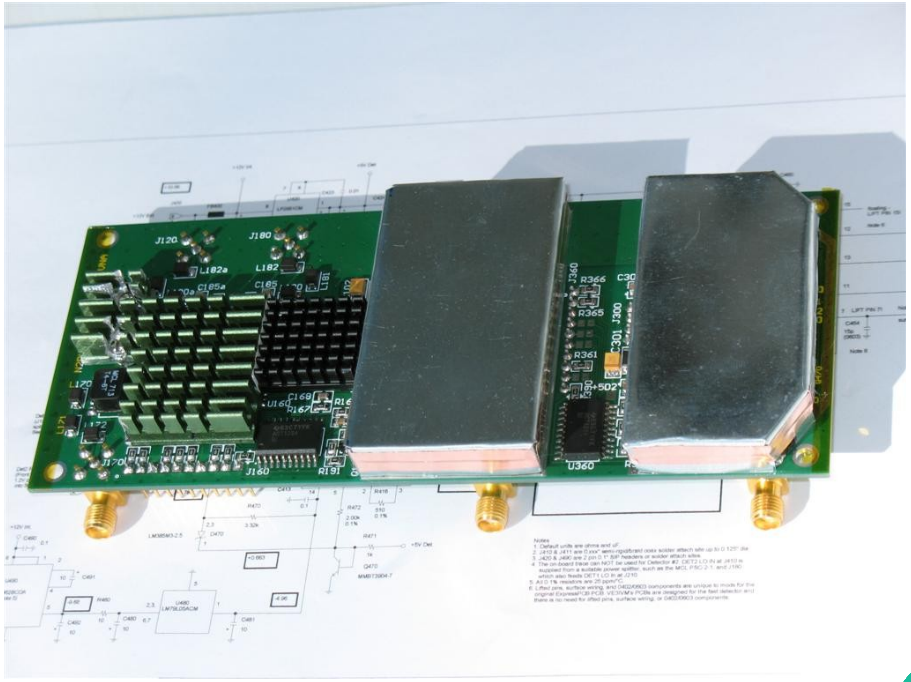
Noise Reduction

Unfortunately, the noise present is not only amplified with the signal, but parts of the receiving equipment generate their own noise through RF interference, shot noise, and Johnson-Nyquist noise. Since all of these noise effects with the exception of interference are thermally dependent, one effective way to reduce the system noise is to cool the components.

Interference can be reduced by shielding the stages that might generate or be susceptible to interference in a grounded enclosure. This dissipates the potentially interfering signal to the ground plane significantly reducing the interference effects.

These methods only go so far in reducing system noise. This is why it is important to move the signal into a lossless digital form as soon as possible.



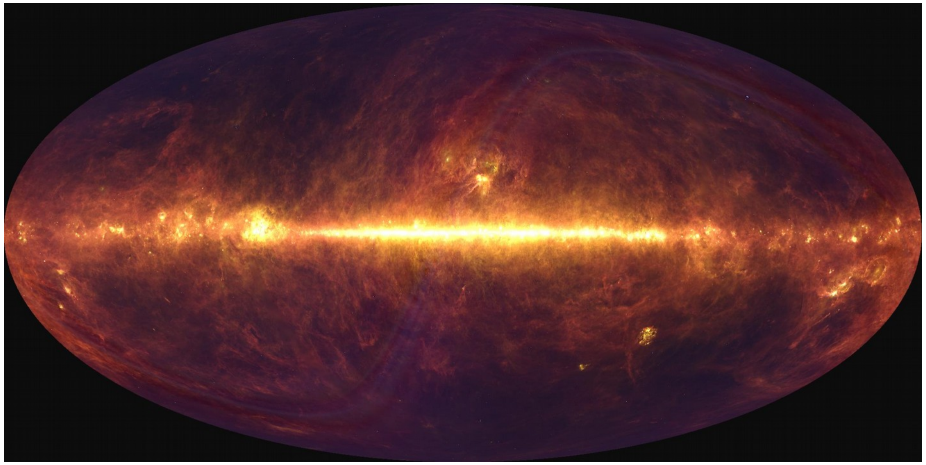


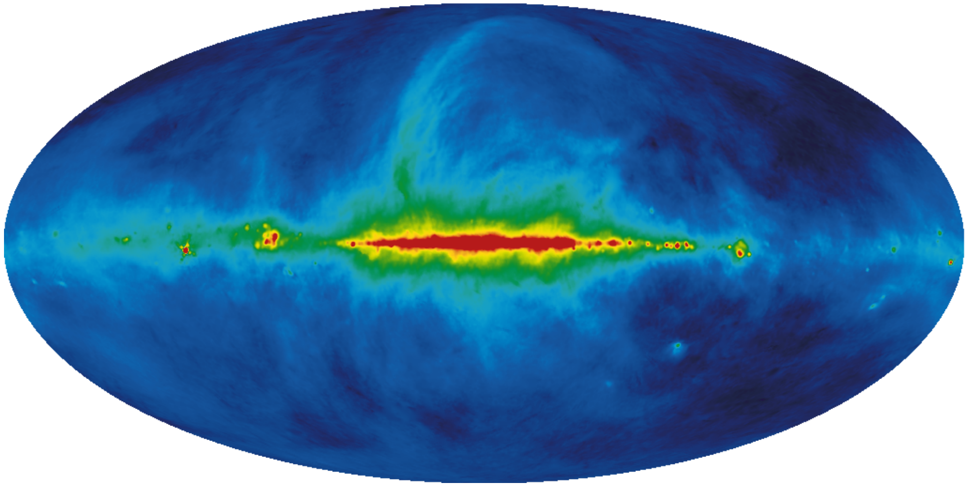
You Can’t Take the Sky From Me

As you might suspect, noise from celestial sources (sky noise) varies by what you are pointing at.

In the image on the right, three radio wavelengths are rendered by three colors. While beautiful, the powerful radio emissions near the center of our galaxy shining brightly will increase the noise floor, making a weak signal more difficult to pick up.

The atmosphere itself can also make noise at the molecules rattle around.





More specific to our scenario, the image on the left shows the sky at a frequency of 408MHz, fairly close to our 437MHz. The colors represent the background noise temperature on a logarithmic scale from 10 Kelvin in black and blue to 250 Kelvin in red. Pointing a high gain antenna with a preamplifier at ISS with the center of the galaxy as a backdrop will increase the system noise by over 3dB.

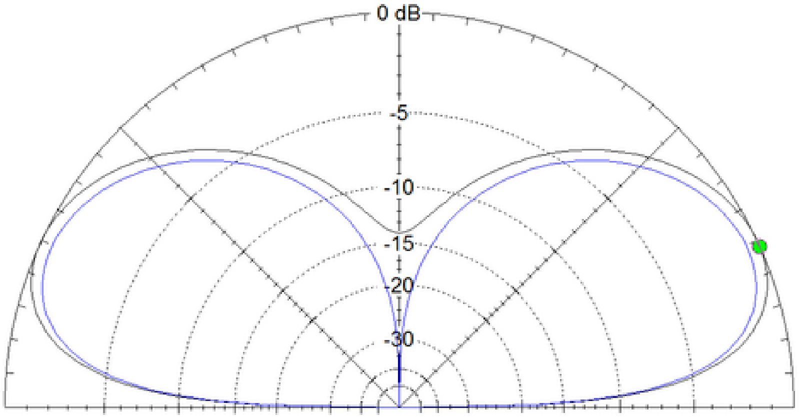
For our purposes, let’s use 15K as our sky noise figure, as this is close to the median.

Antenna Noise

Everything has noise, even the antenna. The trouble is that most antennas also pick upis areas where they are not supposed to. These are called side and back lobes, and inadvertently help the antenna pick up noise from terrestrial sources as well as thermal noise from the earth itself.

Antenna efficiency is a figure between 0 and 1 which indicate how much of the signal is coming from the main lobe (the intended pattern) as opposed to the side and back lobes. It factors heavily into the gain characteristics of the antenna as well. Unfortunately, this figure is not often published since few people understand what this figure represents. It is easier to sell an antenna which yields a 400% boost than saying it has an efficiency of 0.73.

In our example, the antenna has a very wide lobe and 85% of the signal the antenna has converted to electrical power is coming from ISS, and the atmosphere and celestial objects in the lobe pattern and the industrial area near the ground station, the remaining 15% is coming from terrestrial noise and the earth itself. If the back lobe (12%) is picking up the thermal noise of the earth (290K), and one of the side lobes (2%) is picking up an industrial machine at 1200K, this adds a bit of noise to our signal; a function of the average noise picked up on all lobes of our antenna.

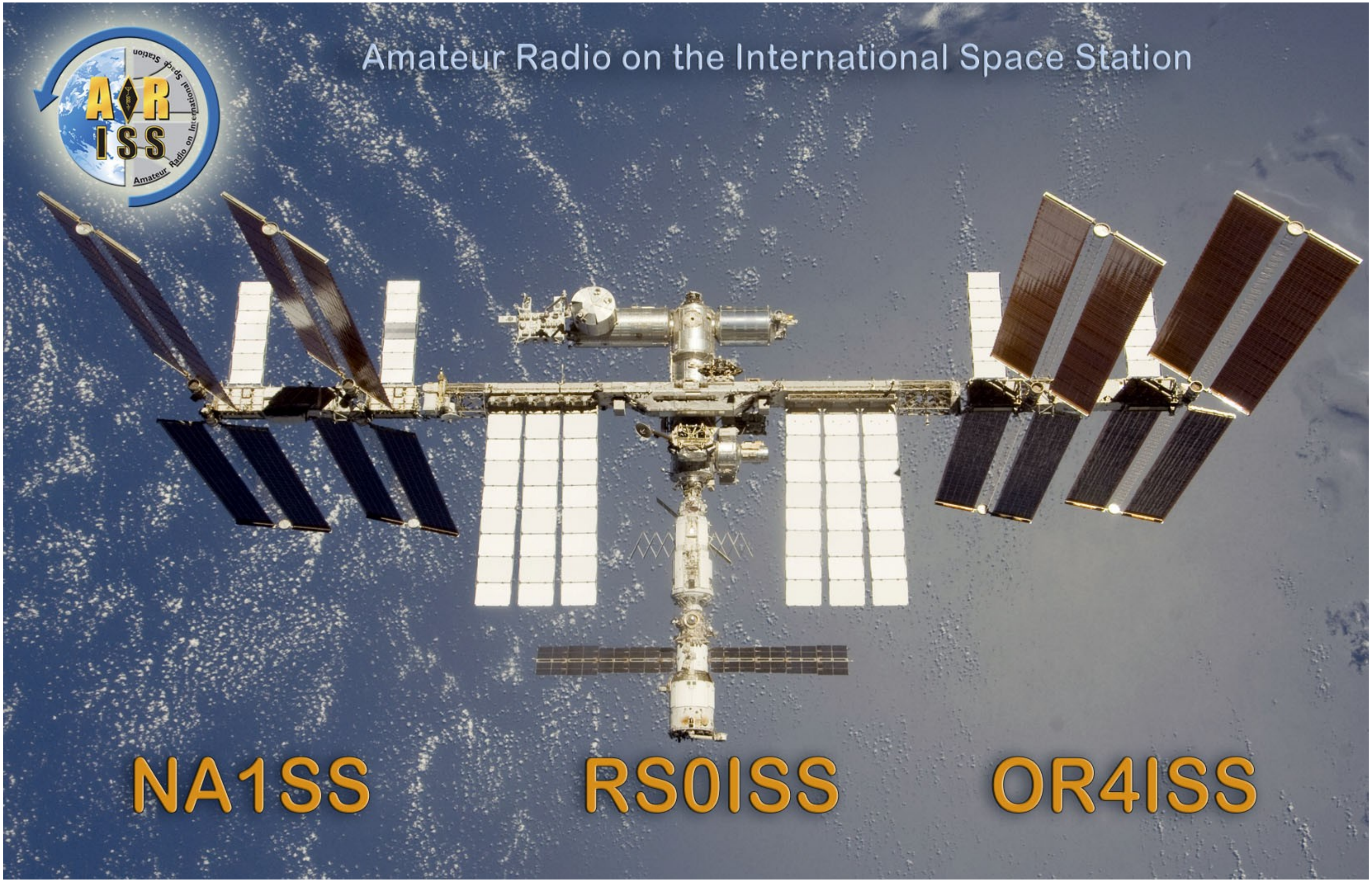


$$\frac{((15K+32K)*0.85)+((15K+32K+290K)*0.12)+((15K+32K+1200K)*0.03)}{3}$$

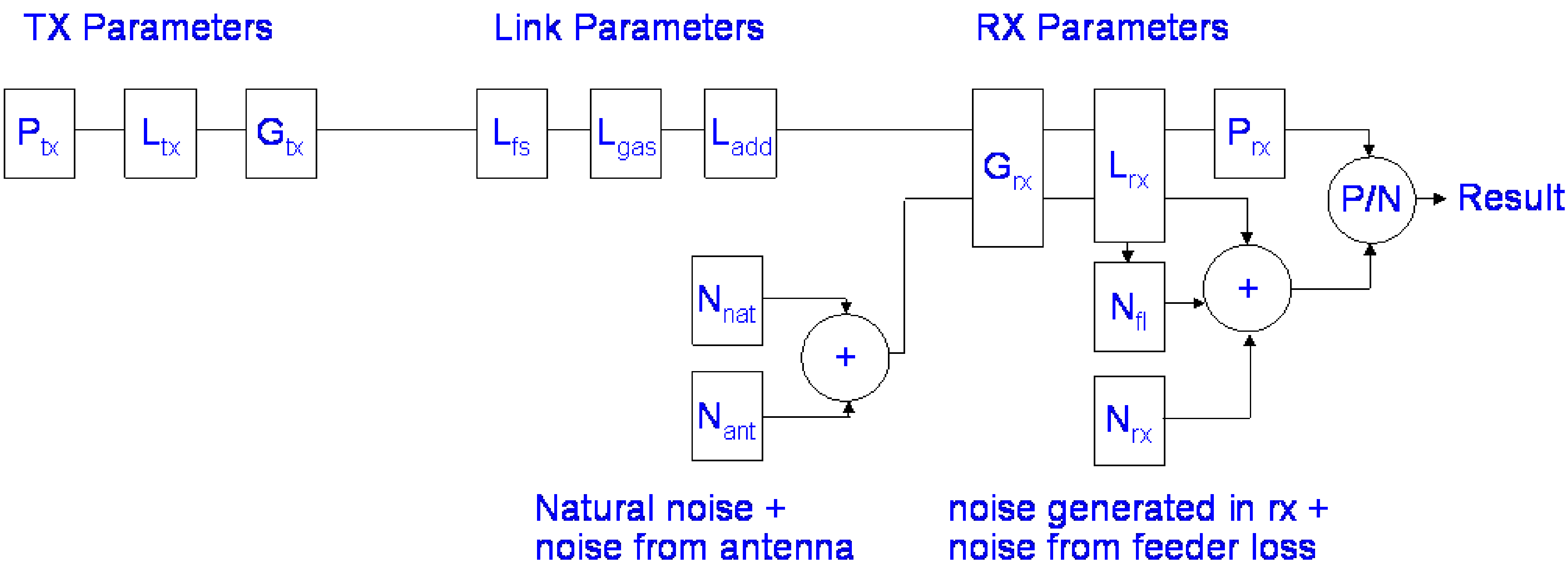
$$\frac{39.95+40.44+37.41}{3}$$

Antenna noise in our scenario, which includes earth, terrestrial, and sky noise sources, comes out to **39.27K**

Bringing it all Together



The Big Picture



Our link budget is nearly complete. We know the signal level received from ISS (-114.37 dBW) and we have a good guess about the noise from the universe around us (39.27K). We also know the gain and noise characteristics of the antenna (+4.6dB), the SDR built in amplifier (+50dB gain, 4.5dB noise) and receiver (-90 dBW sensitivity). Next comes the math to see if the resulting signal will be usable.

Receiver System Analysis

First, the G/T for the antenna itself is 4.6/39.27, or 0.117, which is fairly low. This is before amplification though, and we will revisit this figure at the end.

Since we know that the noise power is equal to the product of Boltzmann's constant, the antenna noise temperature, and the bandwidth of the signal, and we also know the bandwidth of a narrow band FM signal is 10KHz, we get a noise power of $5.419*10^{-18}$ W, which comes to a noise signal level of -172.66dBW or $5.42*10^{18}$ W.

We also know that our received power is -114.37dB + antenna gain, which since the ISS signal is coming in at an elevation angle which has a loss of -3dB on the antenna pattern graph, this results in a gain of only +1.6dB. Therefore the signal an the antenna connector is -112.77dBW, which comes to $5.284*10^{12}$ W.

So far, the signal to noise ratio of 59.89dB looks okay, but we will need to amplify the signal to make it usable since our radio is not sensitive enough by itself to give us a signal we can receive well enough to use. The trouble is that this will also amplify the noise.

Equations and Constants:

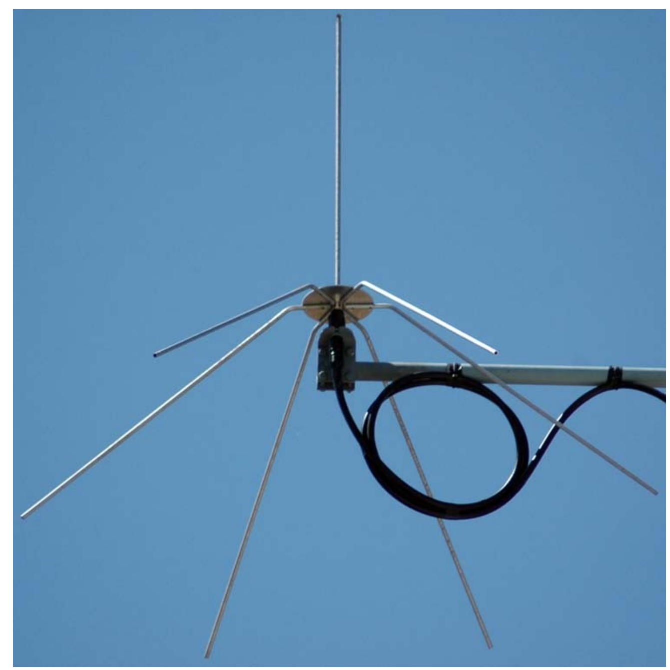
G/T = Gain (in dB) / Noise Temperature (in Kelvins)

Boltzmann's Constant (K) = $1.38*10^{-23}$

$P_{TA} = K*T_A*B$

$P_{dBW} = 10*\log_{10}(P_W)$

$P_W = 10$^$(P_{dBW}/10)$



Bringing the Signal in

In our ground station, The SDR has a built in +50dB preamp stage with a noise figure of 4.5dB.

At this point, the signal from ISS is at -62.77dBW, or 52.844μW, while the noise floor is only at -168.16dBW, or 100nW. Our receiver sensitivity is conservatively rated at -90dBW, which yields a margin of 27.23dB.

This puts the signal to noise ratio (S/N) of the radio signal as received by the receiver at 528.44, or 27.23dB, and that G/T figure from before is now at 1.31, or 1.35dB, which is marginal at best. While the signal could be received, it is doubtful the words would be intelligible.

Preamp Gain: 50dB
Preamp Noise: 4.5dB

Signal at amplifier output: -62.77dBW
Sig. power at amplifier output: 52.844μW

Noise at amplifier output: -168.16dBW
Noise power at amp. output: 100nW

Link Margin 27.23dBW
S/N: 27.23dB
G/T: 1.35dB

The Bottom Line (or TL;DR)

FAILURE! With a link margin of 27.23 dBW, there is a detectable signal, but the low S/N and G/T ratios will make the signal unusable

Some items which contribute to the failure include the antenna type selected and the lack of a low noise amplifier to boost the signal further while managing the noise.

Unfortunately, the HAM radio link with ISS has been suspended, and the radios stowed. Instead, Slow scan TV signals are broadcast, as well as a repeater HAM radio operators frequently use. Both of these require a higher signal to noise ration (S/N) than what this link is capable of.

It should be noted that these calculations do not take into account several important factors which reduce the signal and increase noise even farther:

- Electronic interference from the SDR control computer
- Electronic and inductive interference from the USB port
- Gain reduction due to deformation of the antenna hardware
- Impedance mismatch between stages*

*The RTL SDR is set up for 75 ohm antenna while the LNA is optimized for 50 ohms account for a loss of -6.823dB, bringing down the effective gain of the LNA to +23.177dB. It also raises the system noise by about 0.015dB