frequencies passed.

5. Transmit (downlink) frequency varies with temperature. Due to the wide range of temperatures we are seeing in the eclipse cycle, the transmitter can be anywhere from around 500 Hz low at 10°C to near 2 kHz low at 40°C.

6. Receive frequency has been generally agreed to be about 435.170 MHz, although the AFC makes that hard to pin down and also helps with the uplinks that are off frequency.

We must remember that science is the reason behind these satellites. Not only does science help with the launch cost, it provides a great amount of educational value both from the science payload and in amateur radio itself. The data-under-voice (DUV) telemetry is an excellent way to provide the science without sacrificing the use of the satellite for communications, which would be the case if higher speed downlinks were needed. DUV provides constant science as long as the repeater is in use, which in turn provides more downlink data for the science – a mutually beneficial combination.

Fox-1A is AMSAT-NA's first in a series of Fox-1 CubeSats. Many new techniques are incorporated and lessons will be learned, as with any new product. A total of five will be built and flown. Launches are scheduled for the next three, and a new NASA CubeSat Launch Initiative proposal will be submitted for the fifth. We will incorporate changes from what we learn in each subsequent Fox-1 launch, to the extent possible.

Of the four NASA sponsored CubeSats on the ELaNa XII launch October 8, I am sad to report that ARC1 was never heard from and BisonSat was lost after a few weeks of operation. I extend my deepest sympathy to the people who worked so hard on these projects. To our members, I want to say that we on the Fox Team are very proud and pleased that our first CubeSat is very successful and hopefully will be for some time.

Fox-1 Satellite Telemetry – Part 1: On The Satellite

Burns Fisher • W2BFJ
Fox-1 Flight Software

Fox-1A launched on October 8, 2015, and is now orbiting and operating as new amateur radio satellite AO-85. The first four Fox-1 1-Unit CubeSat amateur radio satellites, Fox-1A through Fox-1D[1], are FM repeaters with 200 bps data-under-voice (DUV), frequency-shift keying (FSK) telemetry and a special high-speed 9600 bps FSK telemetry mode. This article describes the telemetry generation and modulation, as well as the software audio path, in these satellites. In this article, "Fox-1" refers only to these FM/FSK/DUV satellites.

FSK Modulation

In order to describe Fox-1's telemetry, we need to understand FSK modulation and its relationship to FM transmitters. We typically think of FSK modulation as a carrier switched between two frequencies, one frequency representing a digital 1 (mark) and one frequency representing a digital 0 (space). A simplified diagram of this concept is shown in Figure 1 while Figure 2 shows the data versus RF waveform.

But how does this relate to an FM transmitter? Remember that an FM transmitter uses a central carrier frequency that is increased and decreased depending on the amplitude of the modulating signal. If the modulating signal is a square wave of fixed amplitude, then the FM transmitter shifts between two frequencies. We can say that the "high" voltage of the square wave represents "mark," and the "low" voltage represents "space," and we have exactly what we want, the output shown in Figure 2 with an FM transmitter. An FM receiver, which is designed to reproduce the waveform input to the transmitter, would output the same square wave.

This describes an ideal case, assuming infinite frequency response. In the real world, however, signals with fast changes (like the square corner on a square wave) and non-sinusoidal shapes (like the flat top on a square wave) have high frequency content. A typical band-limited FM transmitter/receiver pair, if given a perfect square wave to transfer, would output a signal with rounded corners, "ringing," and wavy tops like Figure 3.

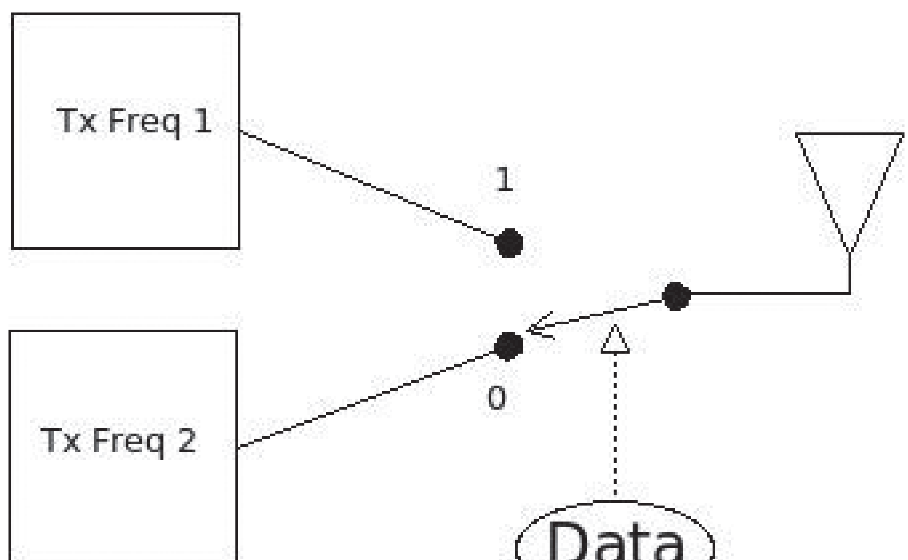

Figure 1 - Conceptual drawing of ideal FSK transmitter

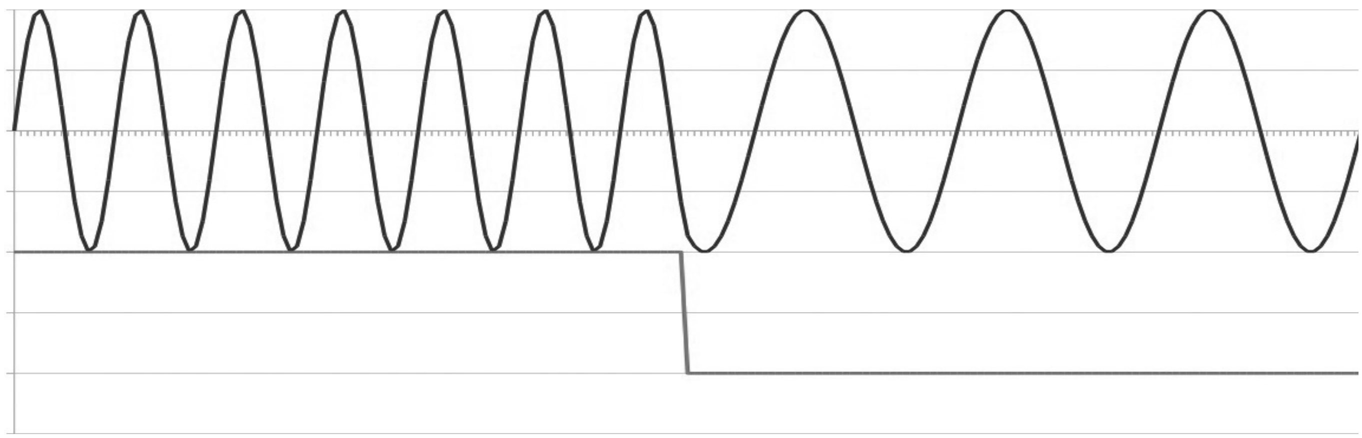

Figure 2 - Data into (bottom) and RF out (top) of an ideal FSK transmitter (not to scale)

Audio Path

Knowing how audio is processed on Fox-1 allows us to see how telemetry is incorporated into it. The Fox-1 designers chose to reduce the number of components on the crowded RF boards by passing the audio path, by default, through the Internal Housekeeping Unit (IHU, i.e. the onboard computer) so that the 67 Hz tone detection, as well as some filtering and the telemetry mixing, could be done in software. A block diagram of the path is shown in Figure 4.

The uplinked audio from the UHF receiver is routed to an Analog-to-Digital Converter (ADC) in the IHU. The voltage of the audio signal is sampled and converted into numbers from 0 to 4095 -- the higher the voltage, the higher the number. The processor then manipulates that data and sends it on to the VHF downlink transmitter by way of a Digital-to-Analog converter (DAC), which turns the samples into voltages.

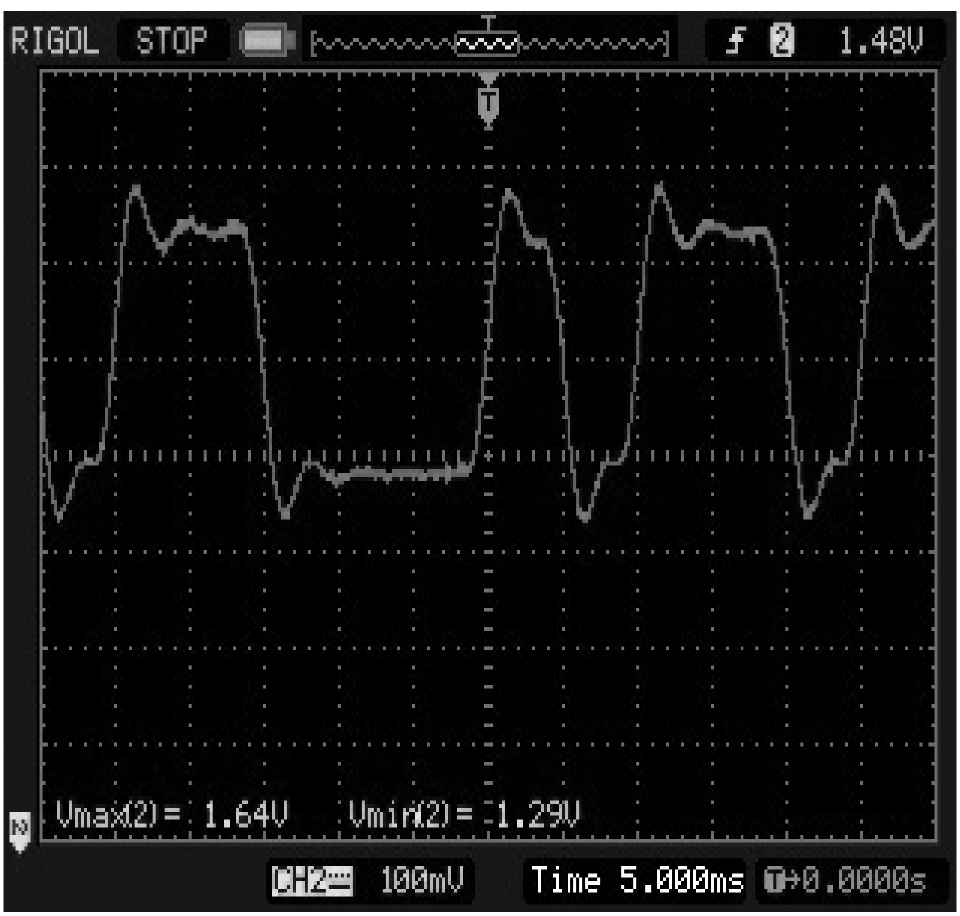

Figure 3 - Frequency limited square waves

Since we plan for the Fox-1 satellites to be operating for a long time, we also designed a fallback in case the computer fails. In that case, there is a direct analog audio path between receiver and transmitter called COR (Carrier Operated Relay). Under COR, the transmitter is keyed when the receiver detects an uplink carrier. The receiver audio is passed directly to the transmitter, with no tone detection and no telemetry.

More specifically, the processor samples the input signal at 48 KHz; 48 12-bit samples per millisecond are delivered to an input buffer via direct memory access direct memory access (DMA). There are two input buffers so that while one is being filled the other can be processed. Every millisecond, the processor performs a number of digital signal processing steps on the samples that arrived the previous millisecond, as follows:

- Reduce the number of samples from 48 to 8 (i.e., a sample rate of 8 KHz) by a process known as decimation. Decimation also acts as a low-pass filter on the signal so frequencies above 4 KHz will not cause aliasing.[2]
- Enter each sample into a signal processing method known as a "Goertzel" algorithm and look for a 67 Hz tone.
- Pass the samples though a high-pass filter to remove any frequencies below around 300 Hz.
- If the transponder is running, the resulting samples are used. If we are sending a voice ID, use instead on-board voice ID samples (pre-filtered to leave a gap below 300 Hz).
- Inject telemetry into the "gap" below 300 Hz.
- Raise the sampling rate back to 48 KHz through interpolation.

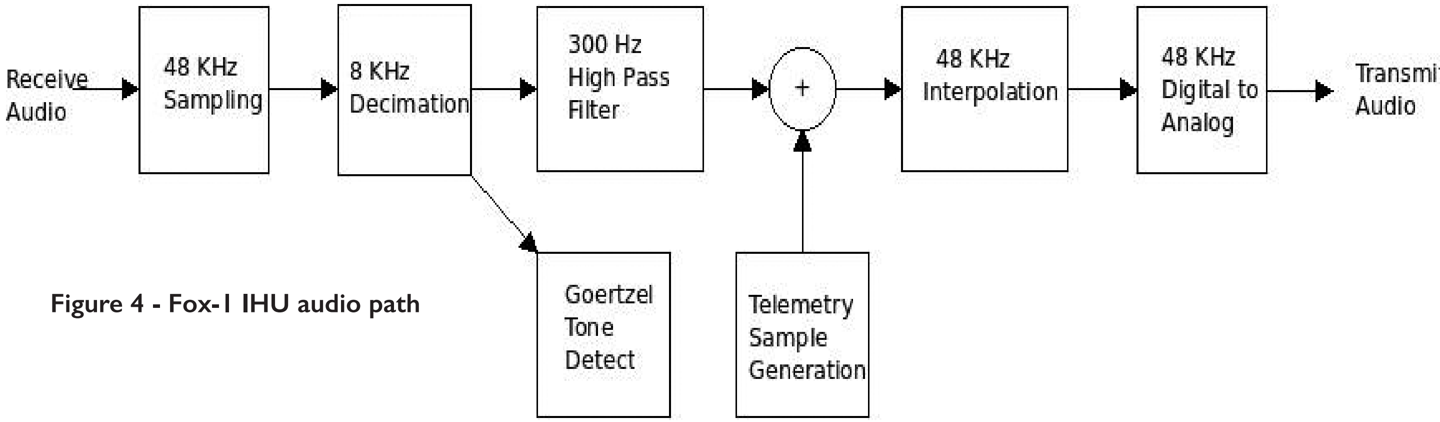

Figure 4 - Fox-1 IHU audio path

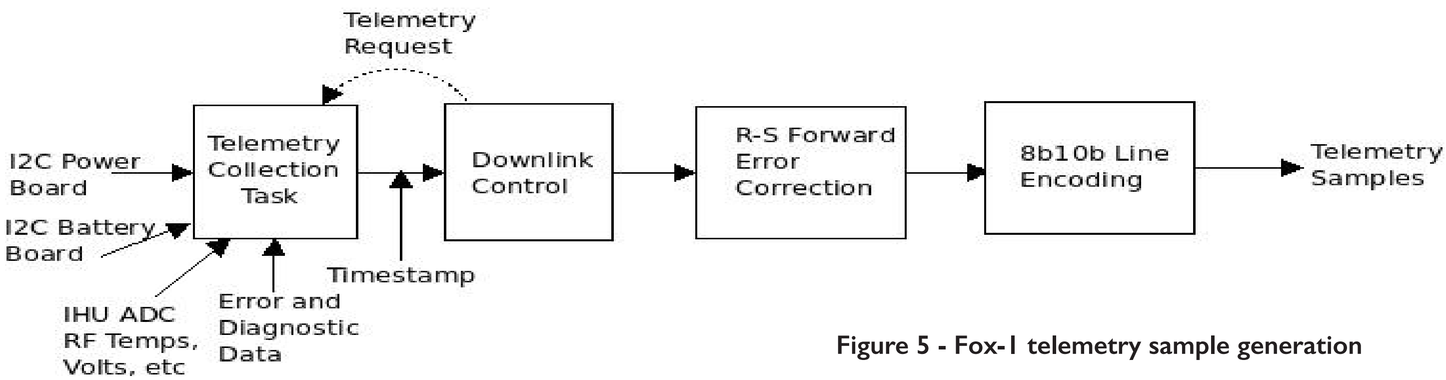

Figure 5 - Fox-1 telemetry sample generation

During the next millisecond, the samples are output via DMA through the DAC to the transmitter. The length of the audio delay in Fox-1 satellites' audio path is 2 ms, broken down as follows:

- 0 to 1ms, input audio is collected
- 1 to 2ms, it is processed, and
- 2 to 3ms, it is transmitted.

The 2 ms time interval is comparable to the amount of time required for an uplink signal to reach an LEO satellite and is unnoticeable to the ear.

Why start at 48 KHz, reduce to 8, and then increase back to 48 again? The reason for 8 KHz in the middle is to reduce the work required by the low-power and fairly slow IHU processor when it performs tone detection, filtering, and telemetry injection. There are several reasons for running the ADC and DAC at 48 KHz. We will see later that high-speed data mode must use the DAC at 48 KHz. The ADC and DAC are synchronized together so they have the same clock speed, and it is simplest to run the ADC and DAC all the time and not switch frequencies. And finally, a 48 KHz sample rate simplifies the analog filtering required on input and output to avoid aliasing issues.

Data Under Voice

To understand how DUV works in Fox-1, first assume that Fox-1 is receiving an unmodulated carrier, so the receiver is experiencing full quieting and is sending no audio to the ADC. In that case, we simply put numerically high samples into the output buffer for a mark and numerically low samples for a space. This makes a square wave and produces FSK modulation as described above.

In terms of the number of required samples, 200 bits of telemetry per second means 5 ms per bit. At 8 samples per millisecond, that is 8 x 5 or 40 samples per bit.

We said earlier that square waves contain high frequencies. However, we only have allocated a bandwidth of 300 Hz for the telemetry. The solution is to use a low-pass filter on the square wave that represents the data, reducing it to about 200 Hz. (The 100 Hz cushion allows us to use a fairly simple and not very sharp filter.) This produces a signal more like Figure 3, with a wavy top, rounded corners and some ringing or oscillation around changes between mark and space. Notice, though, that the signal is relatively stable in the middle of the bit. The decoder knows the spacing of the bits, so it can look in the middle to identify a mark or space.

With DUV, suppose that the uplink is carrying voice modulation. The buffer where we want to put the telemetry already has samples representing the uplink voice. We must decide what percentage of the downlink modulation will be voice and what will be data. If we want 90% voice and 10% data, we scale the uplink samples by 90% and ensure that the data samples we generate do not exceed 10% of the maximum value. Then we simply numerically add the value of each filtered data sample to the corresponding filtered data sample.

What does this mean for the output carrier frequency? Remember that the carrier frequency varies depending on the voltage of the input modulation. By adding the data to the uplink sample, we have increased or decreased the corresponding output signal voltage depending on whether we are adding a mark or a space. This increased or decreased signal voltage increases or decreases what the frequency of the carrier would be without the data. Imagine a graph of the entire carrier frequency versus time shifting higher or lower with the data. You can still consider this Frequency Shift Keying, but it is just not quite traditional.

To decode the data, we use an FM receiver and work with the resulting audio. We use a sharp low-pass filter around 200 Hz (we have more processing power on the ground). Now we have reproduced approximately the data samples that we injected into the audio stream in the satellite. Imagine talking over an audio link with a hum or buzz in the background and filtering out the hum with a high-pass filter or the voice with a low-pass filter. This scheme is completely analogous.

We can now see why you cannot just plug FoxTelem, the telemetry decoder, into the speaker port of your FM receiver. CTCSS tones, which you typically use to trigger a repeater, are in the range of 67 Hz to 250 Hz. Thus, most ham FM receivers filter out these low frequencies so you don't hear them. However, that is just the frequency range where Fox-1 data is located. If it gets filtered out, there is no data.

Many ham FM receivers have special high-speed TNC output ports. Some of these will work fine for telemetry, but you must look at the low frequency specifications for them. High-speed TNC output has reduced or eliminated the low-pass filter to allow high frequencies to pass through, but it still may have a high-pass filter that blocks the low frequencies we care about.

One important point is that, while the data is in the bottom 200 Hz of the audio, when transmitted on FM and mixed with the voice uplink, data is spread all across the FM channel's bandwidth.

High Speed Data

Data mode allows us to send data at 9600 bits per second. The main purpose of this mode is to send data from on-board experiments for which 200 bps is insufficient. For example, Fox-1Cliff and Fox-1Delta will have a camera experiment supplied by Virginia Tech. While AO-85 does not strictly require data mode, we included it to validate the concept. In addition, it gets more satellite health data to us more quickly, which is an advantage during commissioning.

High-speed data is implemented in the satellite as follows:

- First, save some processing power by discarding the uplink samples. We don't spend processor time decimating or filtering them, or looking for the 67 Hz tone.
- The extra processing time is used to collect and encode telemetry and experiment data faster.
- A speed of 9600 bps requires much more than the 4 KHz bandwidth that can be accommodated by an 8 KHz sample rate, so we put the data directly into the 48 KHz buffer. (Note: 9600 bps means .104 ms per bit multiplied by 48 samples per millisecond, which is five 48 K samples per bit.)
- We do not need to filter the data samples because there is hardware anti-aliasing to match the 48 KHz rate.
- With no voice and much less low-pass filtering, Fox-1 data mode is just traditional FSK.

On-board Telemetry Collection

The telemetry collection path in the satellite is shown in Figure 5. Note that telemetry, with few exceptions, gets collected asynchronously from its transmission to the ground. Telemetry is collected every 4 seconds on the satellite, and each value (where it makes sense) is compared with the previous minimum and maximum for that value. If necessary, a new minimum or maximum is stored along with the time (in seconds since last reset and number of resets) that a min or max changed.

The telemetry modulator uses a double buffer scheme so that, when data from one buffer is being transmitted, the other buffer can be filled. When one telemetry buffer is empty (about every 5 seconds while the transponder is on), the modulator uses the next full buffer, while the downlink manager requests the telemetry collection task to return a new packet of the data that is already collected. It is at this point that the downlink time is filled in.

The entire packet of data is now passed through the forward error-correction routines to generate Reed-Solomon check blocks as well as through an 8b10b line coding algorithm (see "Coding and Modulation Design for AMSAT Fox-1", Phil Karn, KA9Q in *AMSAT Symposium 2013 Proceedings*). The buffer is finally marked "ready" for the telemetry modulator to take when it is needed. When the telemetry modulator frees the buffer that it was working on, the cycle begins again.

Telemetry Values

While some telemetry values are true and false (for example "Antenna deployed"), and some telemetry values are encoded states or counts (for example, "Hard error type"), many values are analog measurements that originated from one of several 12-bit ADCs. The data is either collected directly by the ADC on the IHU board or sent by an I^2C bus from other boards. All data are sent to the ground unprocessed. In other words, they are sent as a number between 0 and 4095, leaving it to the ground software to convert them to degrees, volts, or amps.

When low-speed data is being sent, four types of telemetry frames alternate according to a set pattern. Type 1 contains the real time values. These values are current readings on the satellite within the last few seconds. Type 2 contains the minimum values along with a few extra bits that are not required frequently. These are the minimum values that have been seen since the satellite min/max memory was reset by ground command. Type 3 is similar to Type 2 but uses the maximum values. Type 4 contains low speed experiment data. Each high-speed frame contains all of the above types as well as experiment data.

A future article will discuss FoxTelem, our ground-based telemetry decoder, in more detail.

Notes

1. Fox-1C has been renamed Fox-1Cliff in honor of Cliff Buttschardt, K7RR (SK).

2. For those unfamiliar with digital signal processing, you must sample at least twice the rate of the highest frequency component in the input signal to reproduce the signal faithfully. Too slow sampling leads to an error called "aliasing." Our initial 48 kHz rate can reproduce a signal containing up to about 24 kHz frequencies. However, our decimated 8 kHz sample rates can only work with frequencies up to about 4 kHz.