Space Gate Concepts
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Abstract: The Rincon Research FPGA-based system that was to be used for collecting
and processing data from the recent ill-fated CubeSat launch is described. Logistics
permitting, a demonstration is planned. Issues and alternative concepts are discussed.
Potential applications of software radios interfaced to the web with precision time-
tagging and frequency stability are discussed.

Key Words: FPGA, Software Radio, Precision Time and Frequency, Coherent Array

1. Introduction:

What is a Space Gate? Think of it as a radio portal to the universe that can be accessed
by anyone anywhere in the world. What you might do with a space gate is up to your
imagination, and any limitations of the particular space gate that you access.

During the recent ill-fated CubeSat launch, Rincon Research planned to place an 800 kHz
wide tuner so as to simultaneously receive all the 436-437 MHz CubeSats being
launched. The pre-detection (preD) data was recorded to disk in case it was needed in the
future. Unfortunately, the PreD data rate of 4 Mbyte/sec (32 Mbit/sec) was too high for
transmission over the Internet. So the data were reduced to a manageable rate by
spectrally analyzing the entire band followed by averaging and thinning.

The resulting frequency vs. time raster display (Fig. 1) allowed someone with a modest-
bandwidth remote link to display a raster-style picture of the radio waves over Tucson.
This is the Geek analog to a surfer web-cam of the waves off Diamond Head.

There are useful things that you can do with spectral rasters. Like measure Doppler shift
to update obit parameters, see if your satellite is turned on, determine its operational
mode, or measure spin rate. But there is a bigger payoff.

The Rincon Research Space Gate was designed to operate all oscillators and A/D
converters locked to a Rubidium atomic standard. It also performs precision time tagging
of all measurements based on time derived from a GPS receiver. Finally, it was possible
to reference the Rubidium oscillator to carrier phase measurements of GPS. Typically
time is known more accurately than 0.1 microsecond, and it is possible to tie together
multiple space gates into a very long baseline array.

With this technology it is possible devise many interesting experiments, some of which
will be discussed in the section on applications.

Figure 1: Spectra vs. Time Raster
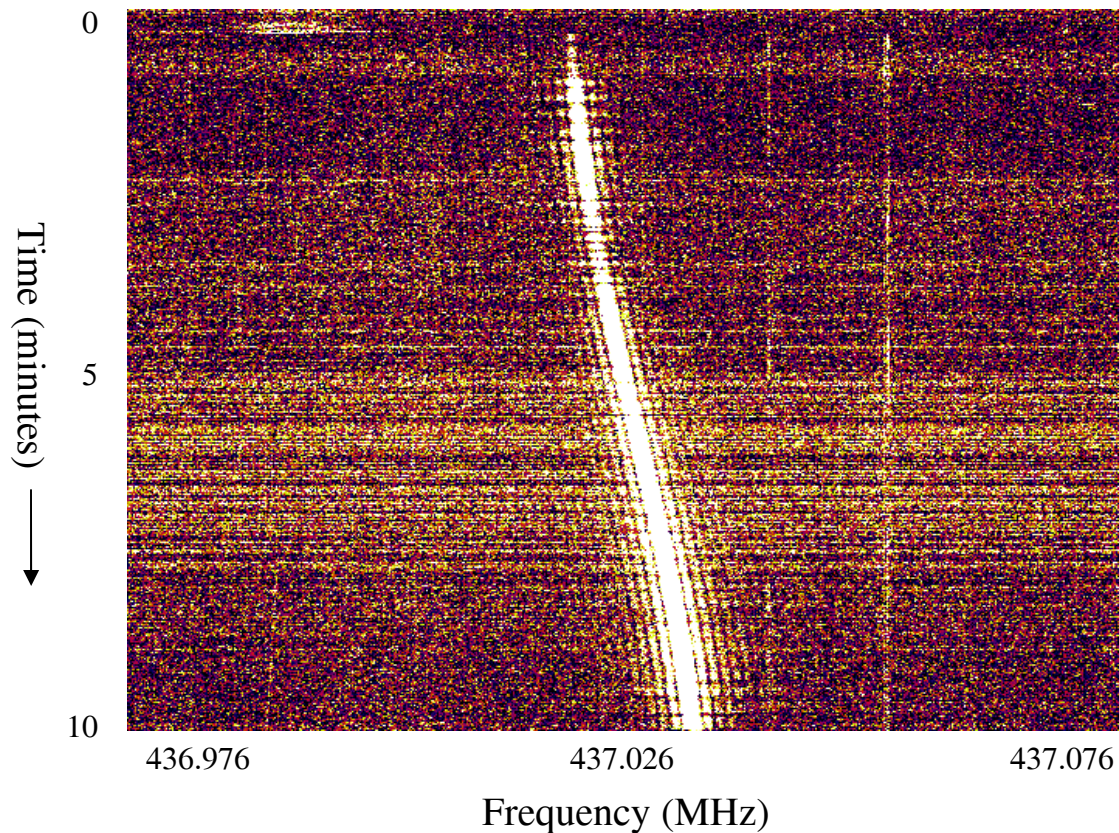
2. Space Gate Data Reduction, and Examples of Space Gate Configurations

A key function of a practical space gate is to somehow reduce the data rate presented to the Internet so that it is manageable. Which of several common ways of reducing the date rate depends on the remote user's needs and practical issues. The common ham receiver solves the problem by passing the desired signal through a narrowband filter that is tuned to the signal-of-interest (SOI) frequency. Since the Nyquist criteria says that a signal can be completely reconstructed by sampling at a rate more than twice the signal's bandwidth, narrowband filtering offers the potential for huge data rate reductions. Taking our 800 kHz CubeSat band as an example, tuning and filtering to 8 kHz bandwidth reduces the bandwidth by a factor of 100. So the first space gate strategy was to allow a user to select the frequency vs. time of the desired signal, and then that could be requested from the stored 800 kHz band.

If the desired signal consisted of very short bursts or was only transmitted for a short duration, then providing the remote requester a snapshot of the full data bandwidth was practical.

Finally, if a demodulator is applied to the filtered signal, it is often possible to reduce the data rate much more. Even though the FSK signal from the UofA satellite required an 8 kHz IF filter (producing 320 kbps pre-D data), after FM demodulation, bit synch, data decision, etc., the resulting data stream was only 1.2 kbps, another reduction of over 100

in data rate. So passing the filtered PreD data through a software demodulator is sometimes highly desirable. But it does require that the correct demodulator be available, selected, and properly tuned.

Figure 2 illustrates the data rates at each stage discussed above.

Figure 2 Data Flow and Data Rate
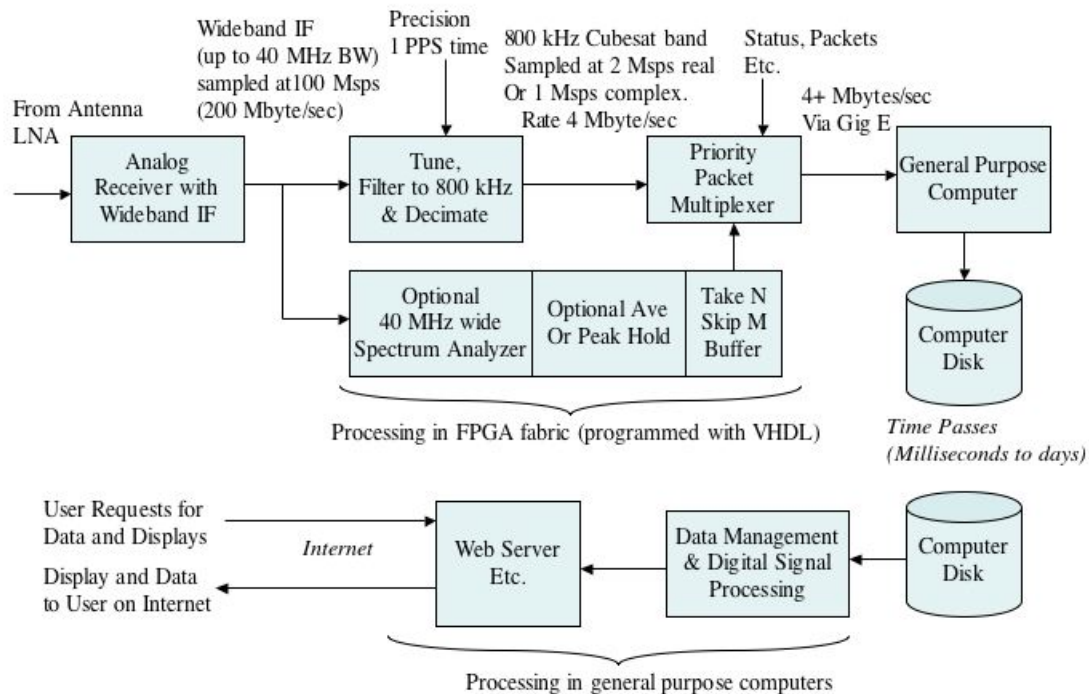
## 2.1 Details of Initial Space Gate

The RinconSat initial space gate configuration is illustrated in Figure 3. The key-processing component in the system was the "Mountain Brik" DSP data acquisition system designed by Rincon Research. This hardware is state-of-the-art and based largely upon using FPGAs for the "heavy lifting" DSP processing. The FPGA technology used is described further at www.rincon.com.

The particular hardware used will bust the budget of the average ham. As technology evolves a design targeted for the ham budget will eventually be possible. For example, since an AR-5000 receiver was used as an initial tuner, an analog bandpass filter 800 kHz wide followed by an A/D sampling at 2 Msps could have been used instead of sampling at 100 Msps and then following the A/D with a 800 kHz wide digital tuner.   We chose to use the expensive approach for two reasons. 1) Rincon Research loaned us a "Mountain Brik" and 2) There are significant advantages to pushing the A/D point as far toward the antenna as possible. These will be discussed later.

Key aspects of the initial configuration diagrammed are:

1. Generic data acquisition and storage tools so users don't have to understand how to program FPGAs with VHDL. These include wideband pre-detection data storage, spectral analysis, precision frequency reference and time tagging,

2. Precision frequency reference

3. Precision time tagging of data

4. "Software radio" approach allows user-specific processing. This processing, which can be changed under user control, dramatically reduces the data rate eventually presented to the internet.

Figure 3: Hardware Configuration of Data Acquisition in RinconSat's First Space Gate
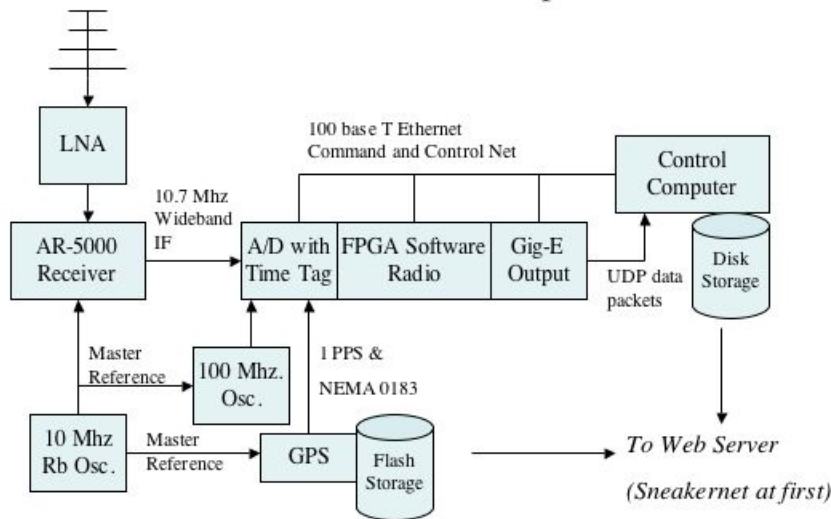
In Figure 3 one can see that an AR-5000 is used as a wideband tuner. The 10.7 MHz IF output of the AR-5000 can be approximately 5 MHz bandwidth. For monitoring CubeSats this bandwidth is excessive, and we sub-band tune and filter to a 800 kHz bandwidth in the FPGA. However for other applications, such as monitoring a TV signal, the bandwidth is barely large enough. In still other applications we may need to process a 40 MHz bandwidth IF, and the A/D clock rate is fixed at 100 MHz to avoid aliasing. We found it convenient to leave the A/D clock rate fixed well above the CubeSat Nyquist rate, and vary the digital sub-band tuner bandwidth in the FPGA.

A 10 MHz Rubidium atomic standard is used as the master oscillator, and everything else was phase locked to it. A stable crystal oscillator calibrated with GPS carrier phase measurements or a GPS-disciplined crystal oscillator would have been cheaper and almost as good, but we used what was available in the system loaned to us.

Precision timing was provided by a Novatel GPS receiver that output 1 PPS time to the A/D converter. An FPGA in the A/D used these 1 PPS time tics do insert precision-time words into the data stream. The second ambiguity was resolved by reading a NEMA-0183 source.

Each of the processing boards in the "Mountain Brik" string has an on-board microprocessor to receive commands and return status via 10 base T Ethernet. FPGA programming is also done via this link. A separate Gigabit Ethernet output sends UDP data packets to the data acquisition computer. Usually the limiting factor in total storage bandwidth is the disk drive on the computer, not the Gig-E output link.

The FPGA can simultaneously generate a number of different data sources. These include thinned snapshots of the raw A/D input, spectral analysis of the entire input, decimated data streams from two variable bandpass sub-band tuners, FM demodulated data streams, and a variety of status and time packets. All of the above are converted to packets, multiplexed through a priority multiplexer, and buffered for transmission.

Note that the packet format described is entirely different from the constant-size UDP packets used for transport over the Ethernet. A lot of thought has gone into what these data packets should contain. If other organizations decide to build similar Space Gates, we urge coordination of packet formats. In the mean time, we will supply details of the formats to users. We also have software available to demultiplex the packets and form simple-to-read files consisting entire of one source of continuous data (plus time information of course).

2.2 Next Step; Direct RF to Digital (eliminating the RF tuner)

If our A/D analog bandwidth were just a little wider, or if we had been interested in a lower frequency like HF, 6, or 2 meters, we could have eliminated the AR-5000 RF tuner. Unfortunately, 436 MHz was beyond our existing A/D's analog frequency range. But that didn't stop us from planning.

The key trick is that the Nyquist criteria doesn't, as is often believed, say that you must sample at twice the signal frequency. It says that you must sample at least twice the signal's bandwidth. So if one samples at 120 MHz (which we plan to do in our next model), a 60 MHz signal bandwidth can be digitized without aliasing. This signal band can be from 0-60 MHz., 120-60 MHz, 120-180 MHz., 240-180 MHz., 240-300 MHz., 360-300 MHz., 360-420 MHz., 480-420 MHz., etc.

Since none of these ham bands are 60 MHz wide, we could select interesting portions of the spectrum with bandpass filters, sum them together, and then digitize the result. For example, the entire HF band occupies 1 to 30 MHz., and the entire 440 band occupies 420 to 450 MHz. After sampling at 120 MHz., the HF band still occupies 1 to 30 MHz., while the 420 to 450 MHz band is aliased by the 4th harmonic of the 120 MHz sample rate down to 60 to 30 MHz. (inverted). Since these are not overlapped in frequency, one can sum the two analog bands together prior to the A/D. Then, after sampling at 120 Msps, on can sub-band tune with the FPGA any signal at HF by tuning 3 to 30 MHz, or any signal from 420 to 450 MHz by tuning 60 to 30 MHz (inverted spectrum).

We may be interested in discrete sub-bands, so even more bands might be digitized simultaneously and covered with only one FPGA. Consider Table 1 that shows the

possibility of aliasing many signal passbands into the same A/D and FPGA processor. The possibility of capturing GNSS data simultaneously with amateur satellite data is especially intriguing for precision work.

Table 1 Example of Aliasing Many Bands Into the Same A/D		
Input Frequency (MHz)	Aliased Frequency (MHz)	Description of Band
1 – 21.5	1 - 21.5	HF band through 15 meters
144 - 148	24 -28	2 meter band
432 - 438	42 - 48	70 cm satellite band (inverted)
50 - 54	50 - 54	6 meter band
902 - 906	54 - 58	33 cm (inverted) weak signal & digital low band segment
		Could trade HF for some GNSS navigation signals.
1176.45	23.55	GPS L5 and Galileo E5a (inverted) Open signal
1207.14	7.14	Galileo E5b Open signal
1227.60	27.60	GPS L2
1278.75	41.25	Galileo E6 (inverted)
1576.45	3.55	GPS L1 (inverted) C/A code is Open signal

Finally, consider that higher sample-rate A/D converters offer the possibility of capturing signals at many different frequencies without relying on the aliasing tricks described above. For example, Rincon Research has deployed a data collection system that captures an entire 500 MHz segment of the spectrum, and this segment can be at any frequency through L-band. Again, this is quite pricey for ham work, but Moore's law and time may change the economics.

2.3 Alternatives to FPGAs

Of course FPGAs aren't the only game in town. General-purpose computers have gotten fast enough to perform significant digital signal processing (DSP) tasks. A common approach is to digitize the pre-D directly into an interface board plugged into the general-purpose computer. Some boards even provide for precision time tagging. It would have been practical, for example, to bandlimit the AR-5000 output with an analog filter and then digitize directly into a small computer for storage and signal processing.

Big advantages of using general-purpose computers are that they are easier to program and more readily available than FPGAs-based processors. It has been said that if you use FPGAs you get 10 times the performance for 10 times the programming effort.

3. Summary and Applications

3.1 Applications

Below is a list of potential applications. It is by no means exhaustive. If you have a cool idea, please share it on the www.rinconsat.com site or contact me directly.

3.1.1 Applications for a single space gate

Operations:

        Precision Doppler tracking of Satellites

        Data recording for post-incident analysis

Education:

        An easily-to-access view of satellites for those with Geekish tendencies

Experimentation

        Precision recording for experiments that require coherency, time, and phase

        Experimentation tool for those that cannot otherwise afford it

        Semi-permanent remote station for local (Tucson) experiments

Long-term goal

        Establish many space gates

3.1.2 Applications for multiple space gates working together

With many space gates working together we might:

        Drive down the cost

        Share development effort

        Operate the gates as long-baseline arrays

        Do many-site coherent monitoring for ionospheric research

        SETI based on time-difference-of-arrival (TDOA) and frequency-difference-of-arrival (FDOA)

        Interference source localization

        Locate and track transient natural phenomena (like lighting)

3.2 Summary

We had two motivations for constructing the Space Gate; to assist CubeSat operations and to provide a semi-permanent precision resource for experimentation. We also thought that it would be useful to make this resource available remotely so we would not have to always be physically present in order to collect data. Once the decision to make it available remotely was made, it was not a large step to making it available to a larger audience over the Internet.

There is a slight conflict between providing a general purpose monitoring function to the public, and performing specialized experiments that might require unique software, measurements, and experimenter control. An example of the conflict arises when choosing where to point a directive antenna. This is not much different from trying to schedule use of a high-power telescope for experimentation while still providing public access. We do not intend to worry too much about this until problems arise, and then try to devise fair sharing strategies.

4. References

http://www.rincon.com (and select FPGA products)

http://www.rinconsat.com/cubesat

https://bach.as.arizona.edu/azstarwiki/index.php/Main_Page

http://cubesat.calpoly.edu/

http://www.esa.int/esaNA/SEMY800DU8E_galileo_0.html

http://www.gpsworld.com/gpsworld/article/articleDetail.jsp?id=61244