Using Digital Communications and Microwaves in Amateur Radio and in the Amateur Satellite Service

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One of the biggest revolutions in technology has been the transition from information being represented in analog form to information being represented in digital form. This transition has profoundly affected communications and media of all types. Photography, music and video recording, documents, telephony, and computation have been fundamentally recast in formats that are compressible, storable, filterable, easily copied, and easily shared.

Digital representations are quite often a series of samples of an existing, natural, continuous analog signal. Imagine you are in charge of a ferryboat service on the Mississippi river. You can't cross with passengers when the water level is too high. You can't cross with passengers when the water level is too low. Water levels vary quickly in the South due to the complexities of the river system and the weather. You have to monitor the river closely. To help with this aspect of the river ferry business, you decide to hire a young up and coming local fellow named Huck Finn. You tell him he has to watch river levels and let the ferry drivers know when they can take passengers or when they have to tie up at the dock and wait for better conditions.

Now, Huck doesn't want to stand there for his entire shift, continuously watching the water levels go up and down. He notices that the fastest the water levels change from safe to dangerous is at least one hour. To be able to properly monitor the river, he figures he needs to check at least every half hour. So, he decides to wind up an alarm clock that sounds every half hour. Every half hour, when the alarm goes off, he'll check the river level and do whatever is required to keep the ferryboats safe. Between checks of the river, which don't take up that much of his time, Huck naps, fishes, reads, talks with his friends, doodles, and works on a couple of side ventures (http://twain.lib.virginia.edu/huckfinn/huchompg.html).

Huck can get away with this because he's checking at least as fast as the rate at which the river makes important changes of state. The rate of checking (sampling rate) is determined by how that particular river behaves. Another slower-changing river might only require checking (or sampling) every 10 hours. Another more tempestuous river might be subject to flash flooding, and needs checking every 10 minutes. Or, possibly, the installation of a bridge!

After a day of leisurely sampling, Huck has a list of river levels. This list of numbers is taken at regular intervals and describes the behavior of the river for that day. In fact, if he checks often enough, and he's willing to do some math, this pocket-sized list can perfectly recreate the behavior of the river.

For modern electronic computerized circuits, Huck's river level numbers would be converted into binary representation. This is base 2, composed of 0's and 1's. If Huck could only measure with an accuracy of 1 foot, and the river level varied from a minimum of 20 feet to a maximum of 27 feet, then he could (if he wanted to) use the following values.

River Level	**One Possible Binary Representation**
20 feet	000
21 feet	001
22 feet	010
23 feet	011
24 feet	100
25 feet	101
26 feet	110
27 feet	111

Huck would probably just use the more human-readable feet (or meters, or fathoms, or whatever). But, if he wanted to show off to Tom Sawyer, then binary would probably do the trick.

Sampling a signal at regular intervals, when those samples are done fast enough to not miss things, is how you digitize. In digitization, the mapping of the sampled signal levels to a digital value, as shown in the table above, is one necessary part. The other is the rate at which you take measurements. The really amazing thing is that the whole analog signal can be exactly reconstructed from just these samples, as long as certain simple conditions are met.

The formal definition tells us that the sampling rate must be at least twice the bandwidth of the band limited signal under consideration in order to reconstruct the signal. Therefore, a 3kHz wide signal must be sampled at least at 6kHz in order to be able to properly capture it. This minimum sampling rate is called the Nyquist Rate. It is named after Harry Nyquist (https://en.wikipedia.org/wiki/Harry_Nyquist), who worked on determining bandwidth requirements for transmitting data.

Nyquist's work provided a solid foundation for Claude Shannon's work. Shannon (https://en.wikipedia.org/wiki/Claude_Shannon) is considered to be the founder of the field of Information Theory. The field of information theory handles questions of error-correcting codes, compression, and determining how much real information can be squeezed into or extracted from a signal.

2016 is the centennial celebration of Shannon's birth. There have been celebrations, documentaries, and many social and technical events to commemorate his anniversary, including a Google doodle! (http://www.google.com/doodles/claude-shannons-100th-birthday)

Digital representations also include artificially created signals. Instead of sampling existing natural or analog signals, the samples are generated by mathematical algorithms or by shifting binary register values. Digitally synthesized signals serve as radio oscillators. Digital synthesizers can create complex arbitrary waveforms that serve as test inputs for circuits and systems of all sizes.

In photography, the film vs. digital debate developed over time (pun intended) with the film crowd responding to early digital sensors by insisting that the resulting digital images did not equal film quality. This was true, especially for the first several generations of digital cameras. However, the ease of storing, sharing, copying, editing, outweighed the relatively low resolution or problems with dynamic range. And then, the sensors started getting better, and getting better very quickly, and very cheaply. Today's digital cameras take insanely good images at a tiny fraction of the cost of film development. Whatever you gain by developing film has to be worth giving up the convenience, ease, quality, consistency, and flexibility of digital photography.

Are there arguments for film photography? Yes, there are. There still are, to this very day! But, digital photography has answered almost all of them. Any remaining application where film is chosen over digital is a question of very exacting (or obscure) requirements, or for the sheer enjoyment of working with a mechano-chemical process. That digital has defeated film is not a completely uncontroversial statement, but one only has to go shopping for cameras or look at the sheer magnitude of published digital photographs to see the effect of digitization on the world of photography.

This same effect has happened in communications. Digital communications are rapidly becoming the standard across the board, getting the lion's share of investment, research and development, and consumer dollars. Digital communications are much easier to secure through cryptographic codes, have superior signal to noise ratios, allow authentication and authorization, can be easily copied, can be easily stored, are much more efficient in terms of bandwidth consumed, can be filtered, and can adapt to link conditions by using different error-correcting codes for different situations. It is much more difficult to do any of these things with an analog signal. So what's not to love?

Any digital signal is more complex, and therefore more challenging to deal with, than almost any analog signal. Any digital system requires components and techniques that are advanced, potentially cost more money, and are more difficult to select, implement, and troubleshoot. In other words, a more powerful feature set comes at a cost, and that cost is complexity. This is a normal engineering trade-off.

For example, you may have noticed that many digital voice systems sound like crap. If you've used any of the ham radio digital voice systems, or commercial radios like P.25, or even a cellular telephone, you know that the voice quality isn't that great. On the other hand, digital systems for music playback range from pretty good (MP3) to essentially perfect. Voice systems can sound that good, too: the better VoIP telephones and the WhatsApp voice memo system are good examples. What's the difference? It's in how the audio signal is encoded for transmission and then decoded after reception. Codec stands for the combination of the words code and decode. A codec is a hardware and/or software element that does both the coding and decoding functions in a communications system.

Coding is done before transmission or storage, and decoding is done after receiving or retrieving. There are two main purposes to coding and decoding. The first purpose of coding is to remove unnecessary redundancy in the samples. This compresses the signal which increases efficiency. This is often called source coding. The second type of coding adds in the right type of redundancy and is called channel coding. It may seem strange to first remove information, and then add information back in, but this added redundancy provides resilience and durability to the signal so that it can make it through daunting noise (a terrible radio link), or radiation effects (which is why I hate space), or physical damage (the surface of a CD).

Source coding is like laundry detergent. It removes dirt you don't want. Channel coding is like fabric softener. It puts back in substances that make your clothes perform better in meetings. With the right type of fabric softener, you don't even have to be in the suit to impress.

Crappy codecs are a big problem for digital voice communications because the auditory experience represents the quality of the entire system. Voice quality is in your face and in your ears. Voice is the radio product. Over-compressing voice when it's not necessary results in harsh or unintelligible audio. When compared to a beautiful warm AM transmission, it's hard to justify digital communications when the sound is so much worse.

The reason for this situation with many digital codecs is greed. Greed is not necessarily bad. We want as much as we can get out of a technology or technique, and if the end result is elegant and suitable and affordable, then no harm is done. Digital is no different. With bonus signal-to-noise ratio provide by the physics of digitization and coding, we then have the power to balance at least three factors. We can reduce the size of the antennas, increase the number of users, or deliver that power in the form of higher throughput or higher quality signals to fewer users. For commercial systems, it's obvious which choices result in more revenue. Smaller antennas and packing in more users!

This has led to the situation of codecs being designed primarily for low bitrates in order to get more users per given bandwidth. There are extensive criteria for judging codec quality, but intelligibility and harshness are much more subjective determinations than bitrate. Therefore, bitrate ends up being the primary distinguisher between different classes of codecs, and the lower the bitrate, the better. Operators (or users, or customers) are expected to tolerate the lowest possible quality of voice in order for the system to support as many signals as possible. The critique of this practice is that voice is a special case. If the quality of the voice is just simply not as good as analog, then why value a digital ham radio experience over an analog ham radio experience? It may be that the over-compressed voice signal in a digital communications system has zero errors. It may be that data files transmitted over this system are error-free. It may be that all sorts of amazing functions could be implemented. But, if the resulting encoded voice signal is unpleasant to listen to, then the entire system is suspect. As amateurs, we can afford to experiment with systems that don't necessarily have to drive to the absolute tolerable limit of voice encoding. We can afford to try out techniques and use codecs that provide a higher-quality voice experience. If the resulting usage of such systems can be shown to be significantly higher, and the reported satisfaction greater, then this information helps digital design in general.

Another challenge with codecs is that many of them are closed source or proprietary implementations. This means you can't see or change how they work or they are expensive to get the rights to use.

Based on concerns about voice codec quality and the commitment to open source technology, Phase 4 Ground recommends CODEC2. You can read about and audition actual samples of these open-source codecs at http://www.rowetel.com/blog/?page_id=452

Digital electronics are complex. What can be surprising is that digital electronics can be so cheap. They are cheap because of the enormous consumer demand for the high performance that digitization provides. Computerization of our world has made it possible to have cheap analog-to-digital converters (the electronic version of our Huck Finn), cheap storage (powerful low-cost memory chips), and cheap computing (Moore's Law).
https://en.wikipedia.org/wiki/Moore%27s_law

These three functions are central to the entire digital vs. analog argument. You have to be able to convert real-world continuous signals to digital samples. You have to be able to store those samples in some sort of memory device. You have to be able to make decisions about and for those samples. With these three things, you can literally do anything.

What do digital microwave communications provide the amateur satellite service?

Microwave bands allow significantly higher bandwidths than any other amateur band. This means a big increase in the number of simultaneous users of any particular payload. Due to higher frequencies, it also means a much smaller antenna is required. Digital can be done on 2m/70cm, and there have been repeated questions as to why can't AMSAT simply put up a digital satellite in bands that are already commonly used. The answer is that satellite bandwidths on 2m and 70cm are very limited in comparison to microwave bands, and are very crowded.

The satellite sub-band on VHF is only 200 kHz wide, and existing and planned missions already very heavily utilize it. The IARU frequency coordinator warns that all prospective users of the 2m band must expect to tolerate interference (http://www.iaru.org/uploads/1/3/0/7/13073366/satellite_frequency_coordination_in_the_two.pdf).

In contrast, the 10 GHz band has a 50 MHz allocation for satellites, and has no existing users.

Band	**Satellite Band**
2m	200 kHz
70cm	3 MHz
5cm	20 MHz each way
3cm	50 MHz

Digital communication allows operators to do things with signals that could not easily be done in analog, such as filter, record, tag, alert, and mute particular other signals. Since we're talking about representing everything as data, communications can be voice, voice memo, text, documents, video, video memo, or whatever data type the operator chooses to send. As long as the receiving station knows what to do with it, or can find out how to receive it, the sky literally isn't a limit.

Digital communication allows for the possibility of authenticating and authorizing use of that payload. Each signal can be required to authorize and authenticate before the communications are passed through the satellite.

Successfully and competently implementing authentication and authorization features, if those features are desired or required by the payload management, is a challenge. If you want to work through a satellite, and that satellite requires authentication and/or authentication, then there will be additional steps to get certified through whatever authority is in charge of that payload. This is an increase in complexity for both the ground terminal and payload operators. Doing authentication and authorization wrong is a huge turn-off. Botching it costs time, energy, and goodwill.

The baseline authentication process for Phase 4 is to use the certification process of Logbook of the World. Authentication has to do with identity. Are you who you say you are? Phase 4 Ground's (currently proposed) authentication process establishes that an operator with a particular claimed call sign can receive mail at the address they gave the licensing authority and in the US that would be the FCC. While this process can be spoofed, it's used to establish that a call sign is attached to a real address that address was on a license application, and the address can be reached by the licensing authority when necessary. This is the baseline functionality that we're including as part of the system approach. If a payload or Groundsat wants more stringent authentication, then they can build that functionality into the system. If they want less, then they can turn off authentication and run the system the same way every satellite has ever run in the past – with zero authentication and zero authorization. Authentication can be required before system use. Re-authentication can be done on a schedule. Re-authentication can be done based off of triggers. The triggers may be based on automatically collected data or on other operators complaining.

Authorization is the question of whether or not the identity you claim to be in the authentication stage is allowed to use the communications resource or not. You can authenticate, and then not be authorized to do something in particular. Authorization in Phase 4 systems is up to the operator of the payload and can be accomplished by white lists, black lists, or anything in between. The default is open access to anyone that successfully authenticates.

Authentication and authorization are not uncontroversial. They are functions that are easily enabled by digital communications. They are not required by digital communications. One can build a digital system that has no identity management and no limits on who or when or how one can access a resource like a satellite. Traditionally, amateur radio communications have been almost exclusively of this type. Your identity is as good as your word, and others can't easily control your signal. It's much more difficult to discriminate against an amateur radio operator, for example, if they can access the same communications resource that you can, without anyone putting them on a list first or controlling whether or not they can be heard. When jammers happen, they are ignored. If you're in the right place, at the right time, with the right gear, you can direction find and possibly locate and possibly report the jammer. When previous authenticated and authorized jammers happen on a digital system that can assert control, then the signal is eliminated by whatever process the control operator is able to use.

Accountability, transparency, and consistent standards are absolutely required in order to avoid any appearance of bias, petty retribution, or discriminatory behavior on the part of the humans controlling the authorization process. It doesn't matter if that process is automatic or manual. Automatic processes can be configured to exclude or promote certain types of users more than others. Re-authorization should be transparent to the operator. Onerous re-authorization requirements whether put upon the operator or the operator's radio, in an effort to exclude or discourage participation, is something that has to be acknowledged as a potential problem for any digital system using authentication and authorization.

There are additional big challenges for microwave digital satellite systems.

As asserted, the equipment on the ground is more complex than analog gear. That's why the Phase 4 Ground project exists. 5GHz/10GHz radios are rare to the point of nonexistent. Radios must be easily built or easily bought (for some definition of "easy"), otherwise the "Five and Dime" satellites and Groundsats (terrestrial deployments of the system) simply won't be fully utilized.

Microwave-band analog transponders may be accessible with radios that are already in circulation or are less difficult to get up and running. That's a fact of technology that is not in dispute.

The goal of Phase 4 Ground is to dramatically increase the number of digital microwave experimenters, operators, and providers of commercial gear, in order to provide radios for all sorts of Five and Dime satellite and terrestrial operations. The end goal is for someone to be able to purchase or build up a digital microwave radio system and put it on the air with minimal difficulty or configuration. Buying a system may be as easy as going into your local ham radio store or ordering off the web. Building up a system may be as simple as "buy SDR brand so-and-so, build this filter and/or this transverter, connect it this way, use these web-apps, then download this GNU Radio flow-graph, then press play".

We firmly believe that the advantages of digital microwave radios outweigh any advantages that analog microwave radio might have. We believe it's well worth the additional complexity to enable advanced communications functionality. Advancing the radio art is what we're supposed to be doing as part of the amateur service. Adding expertise in digital communications certainly qualifies, and is well worth the time and energy required. Education and the opportunity to design advanced digital circuits are primary goals of Phase 4 Ground.

Second is the expense. Satellites are expensive. There are a lot of things that can go wrong with a digital satellite payload. Aside from failures due to the environment, and despite the fact that software can be updated from the ground for certain types of computers, there is increased risk and increased cost here simply due to the nature of digital electronics. This is a risk that has been and will continue to be confronted by all the teams working on the various digital payload projects. Mitigating factors include using radiation-hardened electronics, designing in the right types of redundancy, having quality engineering design and review, and having diverse teams that can bring a variety of backgrounds and viewpoints to a project. Things get missed when everyone thinks alike.

Third is legally being able to discuss payload engineering. ITAR and EAR still greatly affect AMSAT-NA work. Phase 4 Ground separated itself from the Phase 4B payload team (and any other payload team) in order to avoid unnecessary restrictions that would greatly hinder our ability to recruit, document, and publish ground terminal designs, software, and documents. This decision has made it much easier to get things done, but comes at the cost of having to take great care in communicating back and forth with the various digital payload teams.

What are the various microwave digital payload projects? As of today, they include at least Phase 4A, Phase 4B, Cube Quest Challenge, Phase 3E, Terrestrial Groundsats, and several potential digital LEO projects. This is a great start!

Current needs continue to be for volunteers unafraid to code for general-purpose processors (GPPs), digital signal processors (DSPs), and field programmable gate arrays (FPGAs). Volunteers are needed for radio frequency circuits, enclosures, user interfaces, web apps that control the processors that are in these radios, protocol development, forward error correcting codes, and many other fields! If you've wanted to get involved with digital processing, design, or communications, then this is a very worthwhile project with a wide variety of moving parts. The protocol for the downlink is DVB-S2 (and DVB-S2X) for satellite links and DVB-T2 for terrestrial. This extremely popular standard is available for download from the DVB project at https://www.dvb.org/

Phase 4 Ground serves any payload project that complies with the proposed "Five and Dime" air interface. Our project documents can be found on github at https://github.com/phase4ground.

If you want to contribute to Phase 4 Ground then join the mailing list by applying at http://www.amsat.org/?page_id=1121.

The Phase 4 Ground list is open to all who want to contribute to the project.

If you are interested in working on a payload, then use the same form, just specify payload engineering instead of ground terminal work. Payload teams need you too!

A PACSAT Payload For The Entire Sector of the Earth Containing the United States

A major payload initiative has been undertaken by Virginia Tech with AMSAT as a crucial partner to produce a rideshare payload suitable for a geosynchronous satellite (or geostationary if you have one laying around). It is an example of the five and dime (5 GHz and 10 Ghz bands) strategy and with a name made popular by one of the authors (Michelle).

Thompson has pushed forward with a complete air interface specification using a well-known and widely available standard: DVB-S2X. Virginia Tech, Hume Center, has accepted the conclusions and analysis that have gone into producing the specification for the waveform that we would place on a rideshare payload carrying an SDR and transmit and receiver capabilities for 5 GHz uplink and 10 GHz downlink.

We have received a tremendous donation by Rincon Research Corporation of Tuscon, AZ which was founded by Mike Parker, KT7D. We have the complete software defined radio needed for our mission. Rincon designed it with a Cubesat form factor but it is likely the most capable Cubesat communications payload ever talked about publicly. Rincon Research is a top notch research and development company doing lots of complex signal processing for various places but mostly for the US Government.

The Rincon AstroSDR is based on the Zynq 7045 system on a chip (SoC) which is an ARM running Linux attached to an FPGA core in the Virtex 7 family from Xilinx and this is married to a very capable RFIC which is a two channel transceiver capable of tuning low VHF through 6 GHz with reasonable performance. Please view the engineering model in Figures 1 and 2 below.

We can package the AstroSDR for use in our transponder payload and that is what we proposed to our host for our rideshare on a spacecraft being built by Millennium Space Systems, Inc. that you have heard about elsewhere in publicity but this is our very first writing of a journal article.

One of the things we know we need to do is to implement the forward error correction scheme, which corrects the inevitable bit errors that occur when you are attempting to receive a weak digital signal way out in space. As such, we are happy to report that Virginia Tech, Ettus Research, Inc. (a division of National Instruments and responsible for the USRP), and AHA, Inc. a company well known for doing high quality signal processing code on an FPGA, and AMSAT working on the ground terminal have teamed up with financial support afforded to us from Ettus. The goal is to implement a form of Forward Error Correction known as Low Density Parity Check (LDPC) that is extremely powerful, free from all intellectual property protections and available in FPGA firmware code from AHA.

AHA, Inc is based in Moscow, Idaho and a former Virginia Tech Hokie, Juan Deaton, is responsible for their involvement in helping us with this very difficult coding. A small team of Virginia Tech people and possibly AMSAT people will go to the AHA facility. Their goal will be to port the code to the AstroSDR and the USRP using the Ettus Framework for making FPGA code much easier to use in signal processing code by GnuRadio developers as part of their normal "flowgraph" programming.

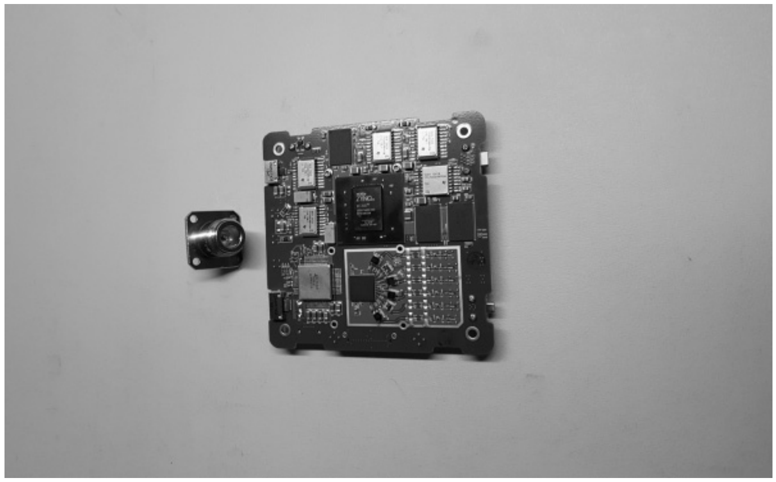

Figure 1: AstroSDR from Rincon Research next to an N connector (side 1)

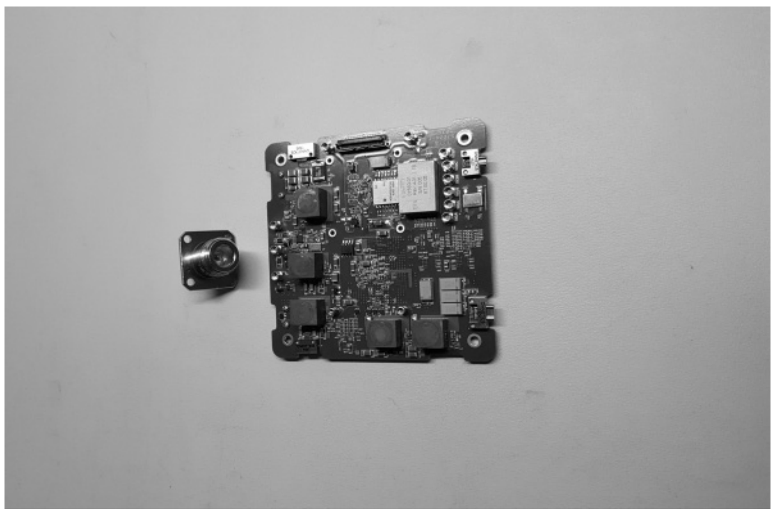

Figure 2: AstroSDR flip side next to an N connector

There remains a lot to do to make this payload fly. But we are happy to report that the entire mission has been approved by the US government and the spacecraft builder and we are entertaining contract negotiations with the US government representative which is managing the contract out at NASA Ames in California.

If you care to read the preliminary design review (PDR) and other materials you may online at VT. Please visit the Phase4B web site at VT that is http://www.hume.vt.edu/geo and consider contributing to the effort because we must raise lots of money to fly but we need a much smaller amount to finish the payload. AMSAT's intention is to use all of what is developed for the Phase4B mission in as many different projects as it can in the future. The full power of SDR is finally available for complex, reconfigurable operation in space from LEO to GEO.

All donations made to the Phase 4B project using the URL provided on the web site above are going to Virginia Tech. As a 501c3 entity, if you are in the US and pay federal taxes, it is a tax-deductible gift. Finally, as an aside, you will see in the report for the PDR that some minor things have been redacted. This is the cost of doing business in an ITAR world.