Smallsat Ground Systems, a C2 to RF Integrated Approach

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Abstract

All satellite ground systems require Command and Control software, data processing, networking and RF Signal processing. Smallsat programs, however, have less tolerance for the complexity and cost points traditionally associated with larger satellite ground systems and more acceptances for new technologies. Additionally, to make ground systems applicable to the small satellite community, one has to adopt a commercial procurement model instead of a program procurement model. This will result in operations capability in weeks instead of months to years; highly integrated, standards based products with well documented APIs that are easy to load, configure and maintain and are easy to expand for mission specific applications. This paper will discuss an approach to developing such a commercial ground system for small satellites.

Smallsats – A quick background.

Small satellites are finding new and disruptive opportunities in today's space industry. Space applications that were once the domain of big satellite systems are finding that they are being augmented and in some cases displaced by lower cost, smaller satellites. The term "Small satellite" can mean multiple things to different people, however for the sake of this paper, a small satellite is nominally a satellite under 500 kilograms. Applications such as earth observation, space to ground communications, and weather monitoring have requirements that can be met with these newer, smaller platforms. The benefits of using small satellites (when applicable) are large; lower costs to acquire, lower costs to launch, and a higher refresh cycle that supports rapid technology insertion as programs and technology evolve. Big satellites programs can take decades to procure, build, launch and operate in today's space climate at price tags in excess of a billion dollars. Small satellites projects can shrink those timelines to a couple of years by leveraging COTS (commercial-off-the-shelf) bus architectures, launch ride shares, commodity flight processors and flight software, software radios, optics, etc. In some cases, small satellite programs have become assembly efforts vs. custom development programs to realize the program goals. However, until now, the ground systems have not kept up with this rapid rate of innovation and reduction in cost. This paper explores how low cost, pre-integrated, software based ground systems can both influence spacecraft program design as well as be cost effective when compared to traditional architectures or building ground systems in house.

Ground System Requirements

Before a proper discussion on small satellite ground systems can begin, the constituent components of a spacecraft (S/C), large or small, ground system need to be discussed. A ground system in general can be broken into three major groups of capabilities, Command and Control (C2), Baseband, and Radio Frequency (RF), shown in Figure 1.

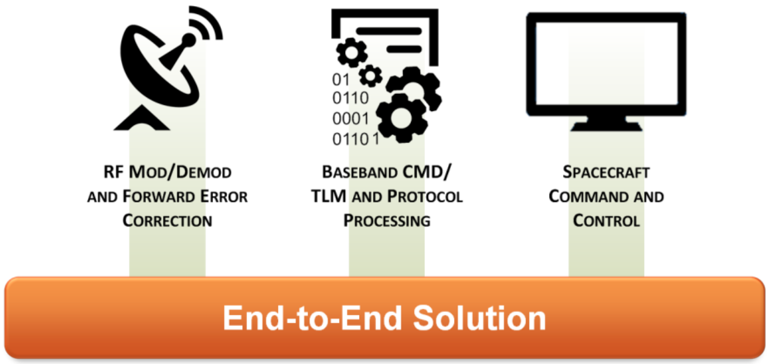


Figure 1. Capabilities Required by a Space Ground System

Starting with the RF subsystem, a ground system needs an antenna and associated electronics for acquisition, tracking, and modulation/demodulation of a spacecraft's RF command, telemetry, and mission data links. The antenna must be properly sized based on the link budget calculations and have the appropriate physical tracking abilities for the satellites orbit regime. For low earth orbits (LEO) operations, the antenna may be smaller but have greater physical requirements for tracking rapidly changing azimuths and elevations due to the high dynamics of a LEO orbit. For geostationary earth orbits (GEO) operations, a larger fixed array may be needed to provide the necessary gain to close the link. In the end, the overall goal of the RF subsystem is to convert baseband bits of data into RF waveforms and vice versa.

The next subsystem in the processing chain is the baseband processing function. In this subsystem, the bits of data from the RF subsystem (in the case of telemetry) or the bits of data from the command and control subsystem (in the case of commanding) are processed and formatted for use for either transmission by the RF system or consumption by the C2 system. Before the advent of standard protocols for communication, baseband processing was often tailor made for the spacecraft being built. The bus was custom, had custom framing formats, and therefore required custom frame processing on the ground within the baseband subsystem. This customization tended to make program costs very high as COTS equipment rarely existed to meet the custom needs. Today even large satellite programs have converged on standards such as those proposed by the Consultative Committee for Space Data Systems (CCSDS) that enforce a particular framing paradigm and error corrections schemes that allow industry to make common use products for these systems.

The final subsystem moving towards the space operations center is the Command and Control (C2) subsystem. In this subsystem, the processed streams of bits have been formatted into operator understandable telemetry health and status, ready for display at an operator's console. Likewise, commands can be issued from the C2 system either automatically or via operator to manage the spacecraft while on orbit. C2 is a vital element to the architecture and deserving of a discussion of its own. For more information on small satellite command and control, refer to Kratos's complementary paper on "A Strategy for Smallsat C2, Systems, Economics, and Scaling to Meet the Challenge".

Typical Ground System Architectures

In a typical ground station, the architecture follows the pattern shown in Figure 2. Of the elements depicted in the architecture, the antenna systems tend to be more expensive and inflexible than the other elements due to their size, power requirements, and physical location constraints. In order to mitigate the need for every satellite program to build its own antenna farm, shared antenna systems such as the Air Force Satellite Control Network (AFSCN) were created to provide a common, distributed antenna system through which multiple Department of Defense (DoD) programs could interface for antenna uplink and downlink services.

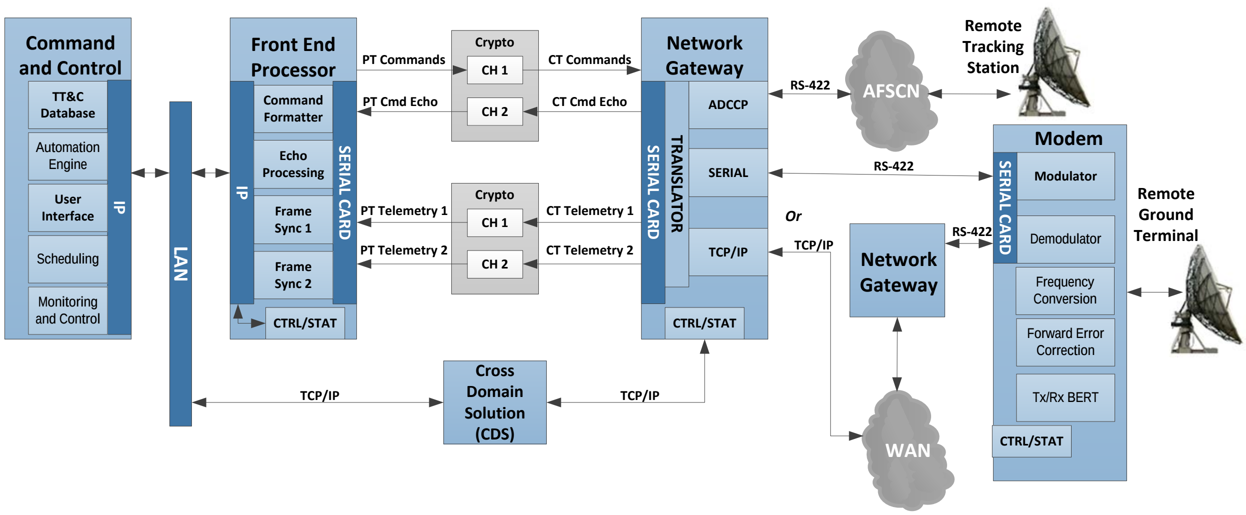


Figure 2. Typical *Traditional* Ground Station C2 Architecture

In Figure 2, the basic elements required to implement a satellite ground system include:

- Telemetry, tracking, and command (TT&C) systems used by operators to issue spacecraft commands and view Telemetry
- Red side Front End Processors (FEPs) that proxy cryptographic gear from the TT&C engine
- Encryption for command link protection
- Network gateways used for deterministic wide area networks (WAN) transport and black side crypto interfaces
- Terminal side gateway equipment to bookend the network
- Modulator/Demodulator systems for narrowband and wideband links
- Up/Down frequency conversion to the antennas and the antennas themselves

Not all satellite programs will require the same architecture, but at some level, each must address all of the functional requirements of the ground system listed in Figure 1. For example, not all space programs will encrypt their telemetry links. For NASA and NOAA programs where the mission is science based, the data is intended to be shared with other institutions and encryption of the downlinks would only get in the way of sharing science data.

The design shown in Figure 2 is generally common and known to be reliable amongst many satellite programs that are operational today. This general ground system architecture is currently in use by programs such as GPS, SBIRS, WGS, Digital Globe, Intelsat, SES, and many others. This architecture can work equally well in small satellite operations in all areas except cost and scalability. The architecture shown tends to drive significant hardware investments, datacenter floor space, and cost associated with procurement, integration, test and sustainment. Scaling to hundreds of spacecraft as some small satellite programs are proposing, can become unwieldy as additional hardware is required to add additional spacecraft contacts. Cabling alone can take significant amounts of installation time as the equipment strings are all pieced together using legacy serial cables.

Reducing Cost in Small Satellite Ground System Construction

Cost is a significant forcing function for small satellite programs causing them to rethink their ground system architectures. In the last several years, there were few alternatives for small satellite programs to turn to in building out their systems. Left to their own devices with limited budgets, these programs went about building their own systems from the ground up using hobbyist level equipment and open source software solutions. Some of these programs found success using this approach. Companies like Planetlabs and Spire have embraced this model. Their success has in fact forced industry to re-evaluate the products they market to these types of customers. In the end, ground system companies are not only competing against each other, but they compete against their customers as they evaluate their make vs. buy decisions. Often these business decisions can be distilled into “cost per bits”. The vendor can win the argument if he can show that his products meet the customers’ needs at a lower price per bit than if the customer were to build the system himself.

It’s also important to evaluate the sustainment costs of the ground system. In most cases, support is needed to fix issues with the software and hardware systems or to make modifications as the ground and spacecraft system evolves. The satellite program needs to determine if it’s more cost effective to maintain engineering support staff for the ground system or to utilize a vendor’s product maintenance and service level agreements to make the necessary changes.

All of these factors combine to influence the make vs. buy decision, therefore for the ground system providers to succeed; they must focus on elimination of cost in the ground architecture on all fronts. Kratos is aware of this trend and has looked into how to drive cost out of the ground system. We believe that cost avoidance can be accomplished through three main tenets:

1. Reduced dependency on hardware based systems

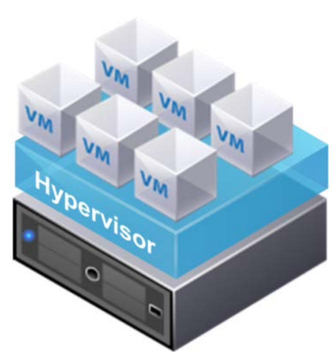
The first tenant focuses on the use of less hardware based systems and more software oriented solutions for meeting ground processing needs. Traditional application of hardware based processing in the ground system typically applies to the modem and front end processing systems. These systems often require custom serial processing boards, a complex chassis, field programmable gate array (FPGA) based modulator(s)/demodulator(s), digital to analog converter(s), and up/down converter(s). Prices are greater on these systems as the companies that provide these components need to cover their costs, which can be high depending on the type of system being used. For example, it’s not uncommon for a narrow band, multi-mission TT&C modem to cost north of $100,000 USD.

Comparatively, software based solutions generally do not have recurring costs typical of hardware based systems, i.e.: maintenance, repair, etc. and therefore have a lower cost of goods sold. This encourages price reduction and can help spur adoption of a particular software solution. Today, many of the typical ground processing functions can be found in 100% software form. Specifically, software modems and software FEPs are common in the marketplace. There are however limitations to these software based solutions. Software performance can be impacted in real time operations and processing limitations are often constrained by the host platform that the system runs on. For example, many older spacecraft programs use a technique called “command release timing”. In this model, the ground system calculates down to the millisecond, the time a command will be received by the spacecraft. Propagation delays both on the ground and through free space, are calculated ahead of time such that when the command arrives at the spacecraft, it arrives at precisely the correct time. The ground systems must operate in “real time” to ensure that no additional delays (i.e.“jitter”) are inserted into the processing since the spacecraft does not keep its own source for accurate timing. To meet a real time requirement like command release timing, the ground system must have a highly predictable processing path. Often these paths are performed in custom hardware to ensure that no delays are incurred (hardware tends to be more predictable than software).

The spacecraft program can mitigate these concerns by moving real time dependencies away from the ground system. Modern spacecraft can include features such as on-board GPS for positioning and timing. This provides a highly accurate time source and avoids the requirement that the ground radio supports ranging which often requires very tight, hardware based timing control. Likewise if the spacecraft has accurate time from GPS, the ground system can issue commands well in advance of time of execution and avoid the custom solutions required for the command release timing problem. Another way to avoid hardware based solutions is to use commercial grade Advanced Encryption Standard (AES) encryption instead of more tightly controlled NSA Type 1 encryption. NSA Type 1 encryption/decryption solutions may force the use of a serial based ground crypto device which in turn, requires a particular hardware based architecture. In short, by focusing on less hardware and more software and being tolerant of the issues software can have by modifying spacecraft design, a small satellite program can reduce ground system costs through this approach.

2. Application of Virtualization Technology.

Virtualization is not a new technology by today’s standards, it is however new to the ground system industry. The benefits of virtualization allow space craft programs to consolidate processing equipment into fewer, yet higher density computer platforms. Virtualization allows ground processing software to run within a minimal hardware foot print; it also promotes use of concepts like Platform As-A-Service (PAAS) offered by non-space companies such as Amazon’s EC2 service or Microsoft’s Azure service.



In order for ground system software applications to support virtualization technologies, the applications cannot have dependencies on hardware systems such as video cards or specific processor instruction sets. The applications must use standard libraries that work on virtual machine hosted operating systems. The Linux operating system excels within virtual environments. In addition to the reduction in physical hardware, management of the virtual environments is simplified since the ground system can be managed using a datacenter approach, common in information technology companies.

By reducing the amount of physical equipment in the ground system, hardware procurement, maintenance, and refresh costs can be minimized to those ground system functions that absolutely must have supporting hardware.

3. Elimination of Integration Labor

The use of software and virtualization technologies in the ground system is instrumental in reducing both hardware and labor costs. Integration and test labor costs represent the largest element of cost in a ground system. This fact is often overlooked as space programs execute. Consider a hypothetical example using a simplified burdened cost for afull-time engineer at $150k per year. Ground system construction will require a hand full of employees, nominally 4 engineers if integrating the system and may double that if building from scratch. The resultant cost for four FTEs at a nominal $150k/FTE/year over a two year period (an estimated and optimistic timeframe given a standard project lifecycle) is $1.2M in integration costs and approximately $2.4M if the program builds from scratch. In addition to the engineering costs are the management and the follow-on sustainment costs of keeping staff employed to sustain the ground system and making improvements/modifications as requirements evolve. This is where industry can provide costs savings; by lowering both upfront costs through pre-integration of COTS software components, compatibility testing with spacecraft radio providers and bus systems, and amortizing sustainment and maintenance costs over multiple users of the same suite of applications. Furthermore, the small satellite program gains from the common experience of the vendor and their extensive experience providing similar solutions to a wide set of users. This approach ultimately reduces risk both in cost and schedule over building from scratch.

In the previous sections we have presented several areas in the small satellite ground system which drives cost to the system. The follow sections will show how using a modular, end-to-end, turnkey approach can not only decrease these costs, but also allow mission planners/developers to focus on their mission.

C2 to RF: A Complete Ground Station Approach

At Kratos, we first realized the need to reduce command and control costs for small satellites by utilizing an appliance approach to command and control. That realization resulted in Kratos's quantumCMD Core C2 product. We also realized that C2 by itself was not a complete, end-to-end solution for the entire ground system in that it only addressed one of the three main capability needs. In 2015, RT Logic, a subsidiary of Kratos that focuses on Space Ground signal processing introduced quantumGND (pronounced quantum "ground") to the small satellite world. quantumGND takes into consideration the needs of the typical small satellite program and bundles the necessary features and functions into a suite of modular software components that realizes a complete ground station from C2 to RF.

quantumGND as a product suite has the following characteristics:

1. Multi-mission Support

quantumGND is not tailor made for a particular spacecraft bus or processing function, instead quantumGND focuses on the most common standards, protocols and waveforms needed by the small satellite world. Much of this industry has been influenced by UHF and S-band frequency spectrums, amateur radio protocols such as AX.25, standards bodies like the Consultative Committee for Space Data Systems (CCSDS), and commonly used modulation and demodulation waveforms. It was these influences that drove the development of quantumGND.

2. Pre-Integration and Compatibility Tested

quantumGND is integrated in the factory before it is even shipped to a customer. This approach greatly simplifies engineering ramp up time to learn, test, and configure the components as well as reducing touch labor, driving down cost. When delivered as a complete C2 to RF system, years of schedule can be condensed to weeks to a fully operational ground system. In addition to component integration, Kratos is working with partner spacecraft radio manufacturing companies, antenna manufacturing companies and others to compatibility test quantumGND's software radio with their products, i.e.: space radios, antennas, etc. The result is that when a customer chooses to use a radio, they will know with confidence that quantumGND works with that solution.

3. Modular Design

For programs that may need to substitute a particular component such as the C2 application or incorporate third party processing functions, quantumGND utilizes a modular design that focuses on open standards like the Object Management Group's (OMG) Ground Equipment Monitoring Service (GEMS) and XML Telemetric and Command Exchange (XTCE) standards. This approach allows replacement of an inline application with another product or customer required solution. In addition to open standards specific to the space domain, web and network based standards such as REST, XML, SNMP, JSON are also supported. This wide breadth of interface support promotes interoperability and ease of use.

4. Waveforms and Processing Support

quantumGND was designed from the ground up to meet small satellite ground station program needs. Through extensive canvasing of small satellite customers, the required set of functions and capabilities of a typical ground system were distilled into the software applications that make up quantumGND. quantumGND consists of three discrete and separate components:

Figure 3. quantumGND Components

Each component is a software application provided as a hypervisor ready virtual machine appliance, complete with operating system and application. quantumGND does include one element of hardware; a SpectralNet Lite digitizer. In all cases, the received RF analog signals from the small satellite must be captured and converted into digital waveforms. Kratos and RT Logic have been investing in digital Intermediate Frequency technology over the last several years. SpectralNet is our digital IF product that converts analog signals at RF frequencies up to S-band into digital IF packets and is shown in Figure 4.

Figure 4. SpectralNet Lite Front End Digitizer

These packets utilize the VITA 49 open standard and are processed by our qRadio software modem. The SpectralNet Lite is a unique, low cost device that provides this digitization front end for the quantumGND radio. The processing capabilities, the baseband processing functions and the RF waveform and forward error correction support, of quantumGND are listed in Figure 5.

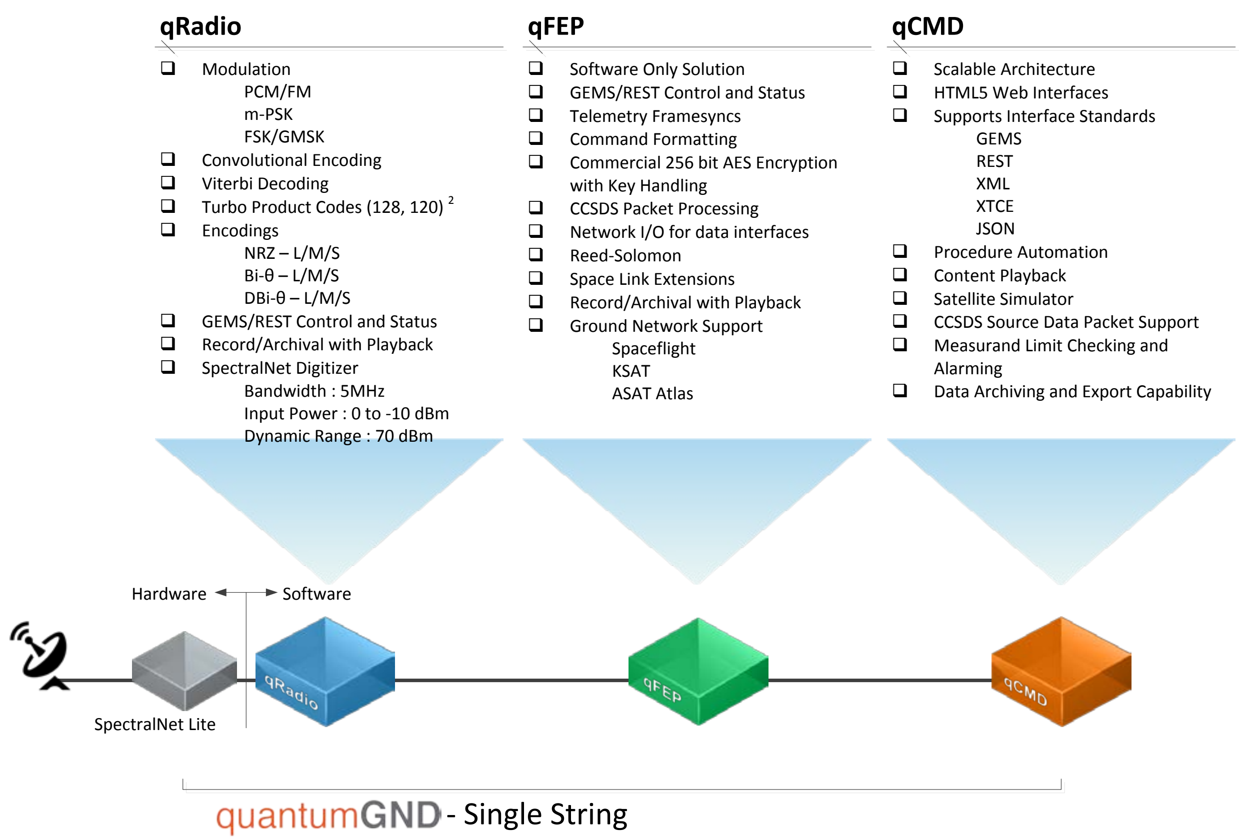


Figure 5. quantumGND Capabilities

Each of these components can be used independent of one another, however the true value in this approach is realized when the three components are used together to form a complete ground system that handles the C2 to RF processing. Figure 6 shows each of the components that make up quantumGND and how they provide the needed capabilities for an end-to-end solution.

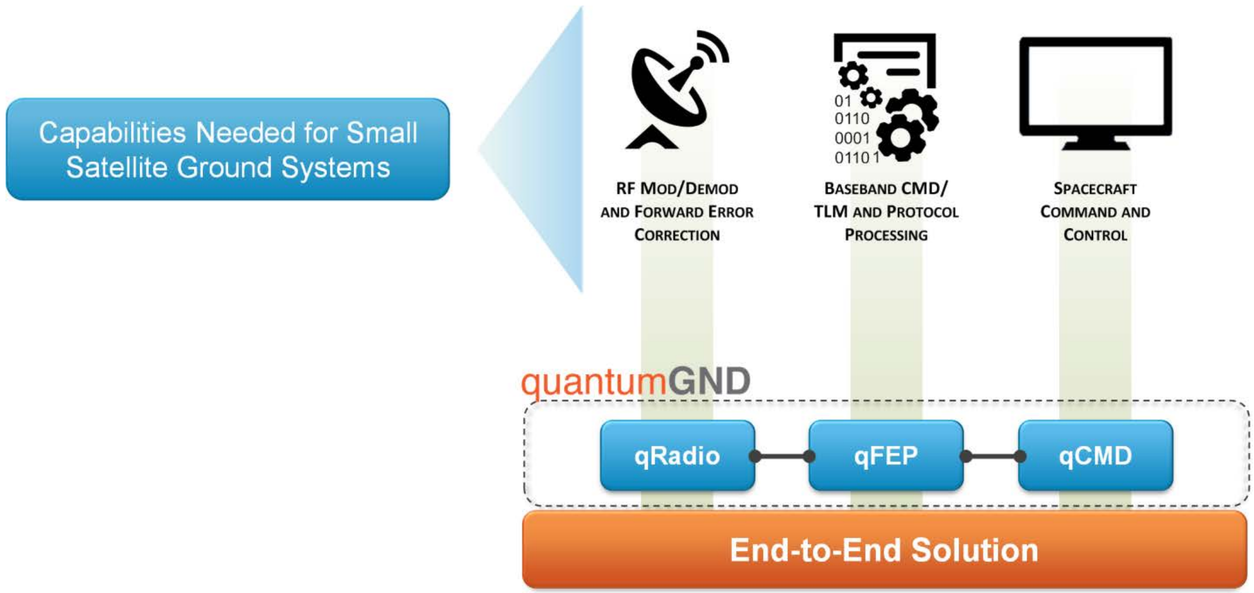


Figure 6. quantumGND: An End-to-End Solution

quantumGND Scalability

quantumGND is designed to support individual spacecraft missions, spacecraft test, and spacecraft fleet operations. Like traditional ground equipment, quantumGND can be utilized in strings of software. Each single string is intended to support contact with a single spacecraft, through a single antenna as shown in Figure 7.

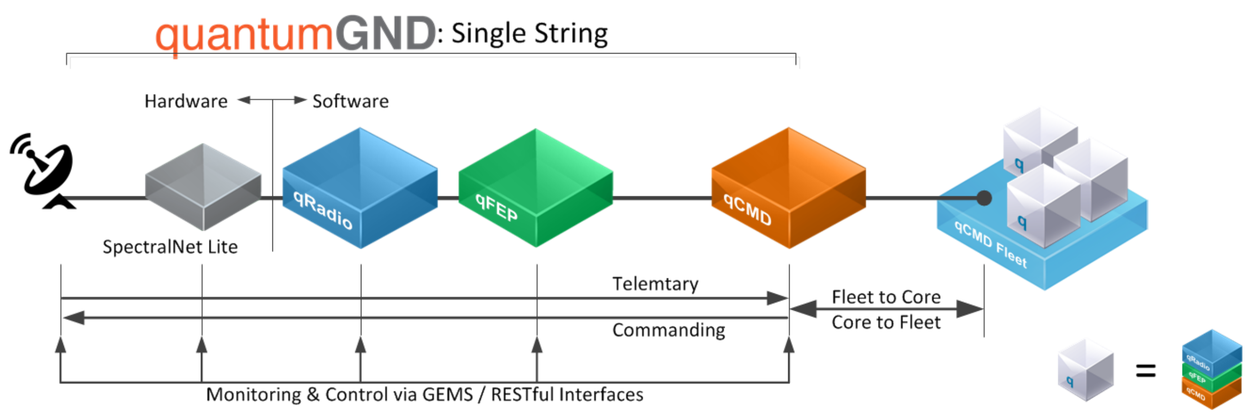


Figure 7. quantumGND Single String

When combined to form strings of ground system processing, quantumGND has the flexibility to expand to support consolidated small satellite space operations as well as support multiple ground antenna sites. Figure 8 shows how quantumGND can be used to support both small local installations a well as larger multi-site fleet operations.

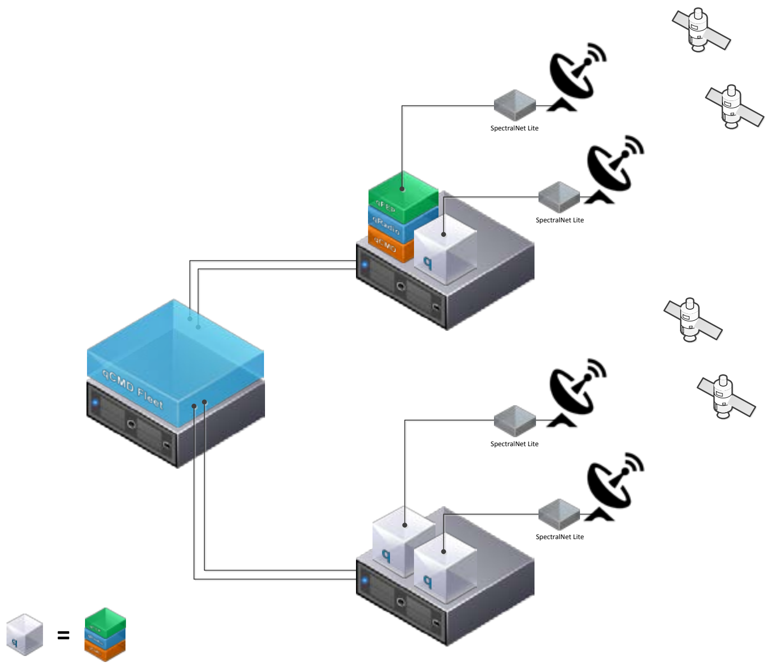


Figure 8. quantumGND Component

The benefit of using this approach over the architecture shown in Figure 2 is great reduction in physical equipment (and cost) as the constellation grows. Since quantumGND uses a virtualization approach, software runtime instances can be stacked on a single piece of high density computing equipment; a blade center for example. The only hardware in quantumGND that must be scaled linearly for additional contacts is the SpectralNet Lite digitizer. The end result is a satellite ground system that using previous architectures would require tens of racks of equipment can be consolidated down to a single small footprint set of equipment that still supports dozens of simultaneous contacts to fleets of small satellites.

Summary

This paper discussed traditional ground systems architectures as well as the main cost and scalability problems associated with using a traditional architecture on a small satellite program. We provided three main tenets for reducing cost and increasing scalability in the small satellite ground system architectures; namely reduced use of custom hardware, use of virtualization and reduction in integration and test labor. We then presented how quantumGND meets these tenets by moving traditional processing out of hardware into modular software, using common standards and interfaces, and integrating in the factory vs. the customer's site. quantumGND presents a compelling approach to small satellite ground systems and addresses the complexity and costs associated with traditional big satellite ground systems for a complete small satellite C2 to RF solution.