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Flying Constellations in the Cloud

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ABSTRACT

The space industry is in the midst of technological upheaval involving the proliferation of small satellites and the commercialization of cloud computing as a service. The proliferation of small satellites is made possible by cube sat standards, normalized small satellites launch vehicles, and continued miniaturization of electronics. The small satellite revolution has created new business, science and defense based opportunities resulting in new proposals for sizeable small satellite constellations. Similarly cloud computing as a service, has made possible the advent of high performance computing platforms and the emergence of commodity virtual machine technology. Hundreds of cloud computing service providers have emerged including Amazon, Microsoft, IBM, and HP.

At the convergence of these two technological upheavals is an opportunity, perhaps even a mandate, to transition traditional satellite group processing from dedicated operations centers to cloud computing centers. By utilizing virtual machine technology, Kratos has hosted a software based ground system with a significantly smaller footprint than traditional ground systems. While this is a step in the right direction and works well for a single satellite or small constellation, the reality is a 1,000 constellation of small satellites is very possible in today's industry and traditional ground processing resources may not be viable solutions.

As a research initiative, Kratos used Amazon cloud computing services to simulate the deployment and operations of a large fleet operations center capable of supporting 1,000 spacecraft with 30 simultaneous contacts and 100 users. This paper will discuss the findings and results of this research and provide an overview of the commercial cloud computing state of the industry including costs, capabilities, and service contracts with their applicability towards satellite constellation operations. It will also discuss the architectural considerations for using cloud computing technology to include Virtual Machine (VM) technology, software tuning considerations, deployment consideration, and security implications.

INTRODUCTION

The concept of blanketing the Earth with constellations of satellites to provide services around the globe is not a new idea having been introduced in the early 1990s. Using space to expand a company's reach to the global market or to connect the remote regions with the rest of the world is a very enticing business opportunity. Companies looking to break into or expand their share of the telecommunications industry were desperately seeking ways to compete with the dominance of the fiber and cable, and space was an untapped opportunity. Unfortunately, they badly underestimated the costs associated with building and launching hundreds of satellites into orbit[8]. These pursuits in the '90s put companies like Teledesic and Celestri out of business and left others such as Iridium and GlobalStar in Chapter 11 bankruptcy[4]. Fast forward almost three decades and we find companies once again talking about large constellations of satellites, this time in the thousands, flying above the Earth to provide worldwide services. This time, however, advancements in technology make it significantly less expensive to build smaller but still capable satellites and launch them into orbit in previously unimagined quantities.

Similar technological advancements have led to the advent of high performance computing platforms and the emergence of virtual machine technology. Both technologies are readily available and inexpensive leading numerous enterprises to combine the two to create cloud computing services designed to provide scalable ground infrastructure without the overhead required to build and maintain that infrastructure. High performance computing platforms and virtual machine technology is not unique to cloud services and many small satellite ventures take advantage of the technology to build their own satellite ground system infrastructure. Ventures delving into large fleets of small satellites, however, may find the cloud services as a more fiscally responsible alternative to the massive ground system infrastructure required to fly thousands of satellites.

A traditional satellite control ground system requires basic elements to perform three general functions: command and control (C2), baseband, and radio frequency. Historically the architecture required for this functionality tends to drive significant hardware investments, datacenter floor space, and cost associated with procurement, integration, test and sustainment. Scaling such a ground system to support constellations numbering in the hundreds or thousands quickly becomes unwieldly. New products on the market, however, now provide much of the ground system functionality in software applications. Gone is the need for dedicated hardware strings tied together with miles of serial cables. New modular software allows satellite operators with the flexibility to re-architect their ground systems to take advantage of the services being provided across industries, including cloud computing. Costs to operate a satellite, or fleet of satellites, is now being driven down even further by eliminating the need for a high maintenance, cumbersome, and geographically locked operations center.

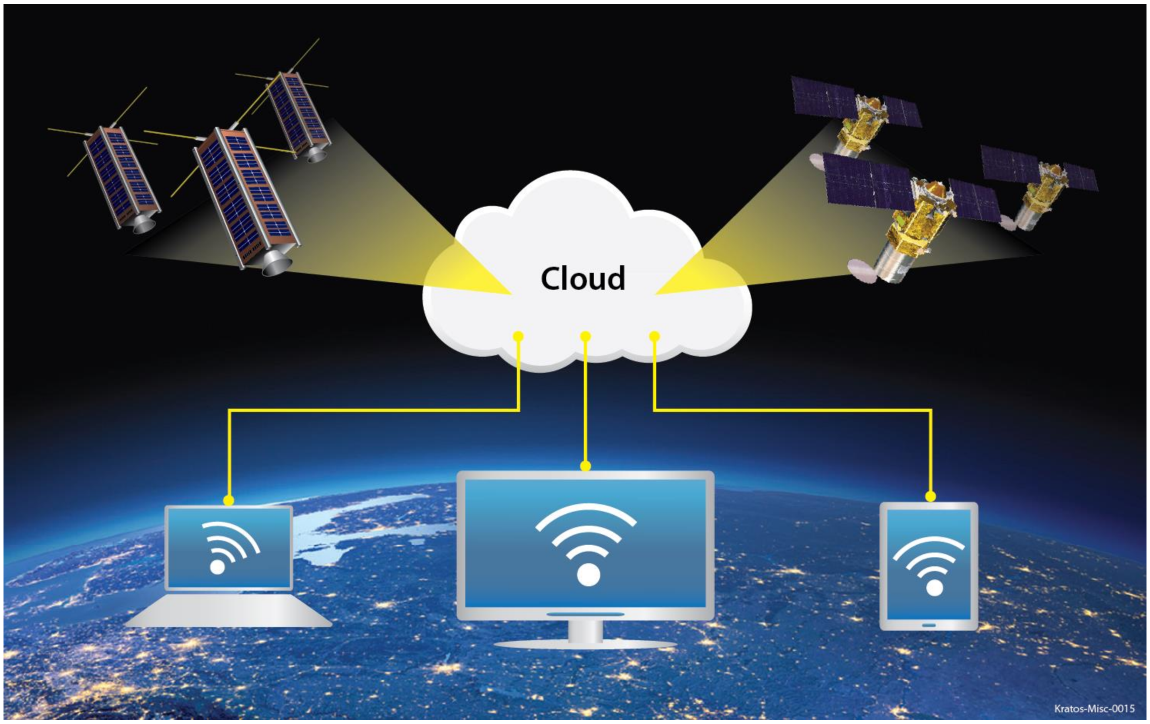

Figure 1 - Technological advances create an opportunity to transition traditional satellite group processing from dedicated operations centers to cloud computing services.

SMALL SATELLITE CONSTELLATIONS

The continuing advancements in the small satellite industry, including more capable small spacecraft as well as less expensive and more prolific launch vehicles opens up more global opportunities. Providing communications and Internet access to remote locations of the world where typical ground networks do not reach or providing coverage in previously unconnected places, such as on commercial airlines, have companies scrambling to put satellite constellations in orbit to capture their share of the market. The Federal Communications Commission (FCC), in response to filings from OneWeb and Boeing, set deadlines for satellite operators to present plans to operate in the same bands as the two companies. As of these deadlines, upwards of 14 companies have submitted applications for Non-Geosynchronous Satellite Orbit (NGSO) operations, totaling 8,731 satellites.

At the forefront of this race is satellite telecomm startup OneWeb, who announced in June 2015 its plans to launch a 648 small satellite constellation to provide global Ku-band broadband connectivity. Even more recently OneWeb reportedly received a pledge of $1.2 billion in funding from Japanese Softbank and will increase the initial satellite constellation by 1,972 spacecraft[11].

The company with seemingly the largest vision is SpaceX, who is proposing 4,425 global broadband satellites in an effort to grab around 10 percent of the global Internet traffic[4], beginning with as many as 1600 satellites for coverage of U.S., Puerto Rico, and the U.S. Virgin Islands and a final 2,825 satellites to provide continuous coverage over the entire globe[7]. The SpaceX constellation would rely on Ka and Ku band for terrestrial and space communication with laser communication between satellites in orbit[10].

Traditional satellite operators and manufacturers are also realizing that in order to remain competitive in today's emerging satellite opportunity-rich environment they must cut costs and are adopting small satellite innovations. Boeing is proposing a 2,900 satellite constellation starting with 1,396 for commercial and government customers[6]. If the business plan is justified an additional 1,560 will be launched[3].

Even the government is beginning to realize the benefits of small satellite constellations as NASA is planning on a number of smaller constellations for earth observation missions to monitor weather and research atmospheric changes. The Cyclone Global Navigation Satellite System (CYGNSS) is a constellation of eight identical satellites planned to fly in formation over hurricane prone areas to monitor weather and improve forecasting abilities. Radiometer Assessment using Vertically Aligned Nanotubes (RAVEN) is predicted to someday "swarm" the Earth with 3U CubeSats to monitor greenhouse gas effect and climate change. Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats (TROPICS) will use twelve CubeSats to measure and track air pollution[13].

While the development and launch of these constellations may present considerable obstacles for these companies and the many others with similar ambitions, the ground systems required to operate or fly constellations of this size are an equal if not more daunting challenge. The sheer amount of data processing and transport involved in supporting dozens if not hundreds of simultaneous satellite contacts demands more innovative ground system solutions than traditional satellite operations centers. Traditionally, a single string of front-end processors, encryption hardware, network gateways, software servers, and user workstations are required for a single satellite contact. Operations centers house much of this equipment in a large, dedicated computer room with rows of server racks that ~~may support~~may support approximately 10 simultaneous satellite contacts and complex mission control software with associated equipment and multiple contacts. Multiplying this architecture to meet the needs of a constellation on the order of what companies are now proposing is simply not feasible with respect to the hardware costs, footprint required, and operations/maintenance costs.

CLOUD COMPUTING SERVICES

Cloud computing is the on-demand availability of computing power, data storage, applications, and other IT resources via the Internet with a pay as you use pricing structure[15]. Cloud service providers assume the upfront investment of hardware and the long-term maintenance of the infrastructure allowing the cloud users to focus their time and money on the mission of their business. Users eliminate not only the upfront costs and effort of building out their infrastructure but also take the guesswork out of determining needed capacity. Cloud services are designed to scale easily and quickly to the computing or storage needs of the user, allowing a business to only pay for the resources it uses at its needs fluctuate.

Services

As cloud providers have matured the services offered, those services have evolved into three distinct categories: Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). Each category employs different deployment methods and thus offers different levels of control, flexibility, and management.

Infrastructure as a Service provides the hardware "backbone" including computers (virtual or dedicated), storage and network access upon which users can deploy and operate their systems. Users have the most flexibility with IaaS and retain management of their own operating systems and applications[16].

Platform as a Service adds the operating system to the services provided, eliminating the users need to procure or maintain that additional layer. Users then are left to focus on the development, deployment and/or management of their mission applications[16].

Software as a Service provides the end-user applications eliminating all product procurement and management responsibilities. Users simply need to focus on how they are using the application for their own purpose or needs[16].

Benefits

Trading the cost of building and maintaining the infrastructure required to operate a satellite ground system in exchange for leasing the computing resources needed is the most obvious benefit of using cloud computing services. Although the actual cost savings could vary greatly depending on the actual needs of a satellite mission, the elimination of the upfront costs for servers, workstations, racks, cabling, or even the floor space to support an operations center is significant no matter the size. Additionally, maintenance and power considerations to operate the system also add a longer term cost to be considered. Actual costs also vary by provider with most offering different options for purchasing use including rates by the minute, hourly, by computing power (CPU and/or GB RAM), or even long-term contract plans. Users with a more consistent and longer usage requirement may realize even greater savings by committing to a long-term contract versus paying for usage on-demand[2].

For those users whose usage isn't consistent or is initially unknown, the immediate scalability offered by a cloud provider can prove invaluable. Rather than paying for idle infrastructure~~, or~~, or not having the infrastructure available when needed, most cloud providers offer the ability to add or decrease computing power or storage within minutes. In these instances, the benefit is not only in the potential cost savings of only paying for what is needed but also in the reassurance that the infrastructure is available when needed.

The flexibility benefit of using cloud services is manifested in a number of ways in addition to the ability to scale computing and storage usage to meet demands. Cloud service users reap the benefit of not only having their applications and data hosted by another organization but also the ability to share them with other users or customers over the Internet. They are not tied to a specific location due to the location of their system but instead employees can easily work remotely, collaborate with colleagues who are geographically separated, and support customers all over the world. For satellite operators, they can easily connect with antenna providers, deliver data to customers, and share situational awareness with their clients. With the proliferation of mobile devices in today's business world, the ability to access data and work from any location is further enabled by the cloud.

Collaboration tools offered by many of the cloud service providers enable customers to work together remotely while managing and tracking efforts. File management applications, developer tools, security management, and analytical tools are a small sampling of applications service providers offer users to further enhance their experience within the cloud.

Concerns

Many of the benefits of ~~usingcloud~~using cloud services come with a compelling concern as well. Relinquishing control of your system may be a huge cost savings but it is at the tradeoff of trusting someone else to adequately maintain the infrastructure your system operates on. A cloud user may reap the benefit of not having to perform that maintenance but they will pay the price if that maintenance is not performed or is performed inadequately. Similarly, hosting your applications and data over the Internet might increase collaboration between employees as well as your customers but arguably, doesn't it make that data less secure? Many of the concerns related to the use of cloud services are not really specific to clouds but more so to doing business over the public domain that is the Internet.

Security measures continue to become more robust but they do so as a result of a higher number of data breaches and loss of data. Cloud service vendors continue to improve their security and many do have very good track records for securing their users information. The fact remains, however, that cloud vendors are high value targets due to the high concentration of businesses and data within the clouds[17].

Legal concerns also must be considered when considering using cloud services for data storage. Regulation of certain data requires companies to know where the data resides, who is allowed access to the data, and how the data is being protected[17]. Intellectual property or data rights are other areas anyone considering using cloud services should be aware of and ensure that any terms and conditions when contracting with a cloud vendor properly protect the intellectual property or data rights.

Since access to the cloud is via the internet, not only is a user's access controlled by the cloud service provider but also by that user's Internet Service Provider (ISP). While theoretically no system can guarantee 100% availability, what level of availability is acceptable depends on the concept of operations for each mission.

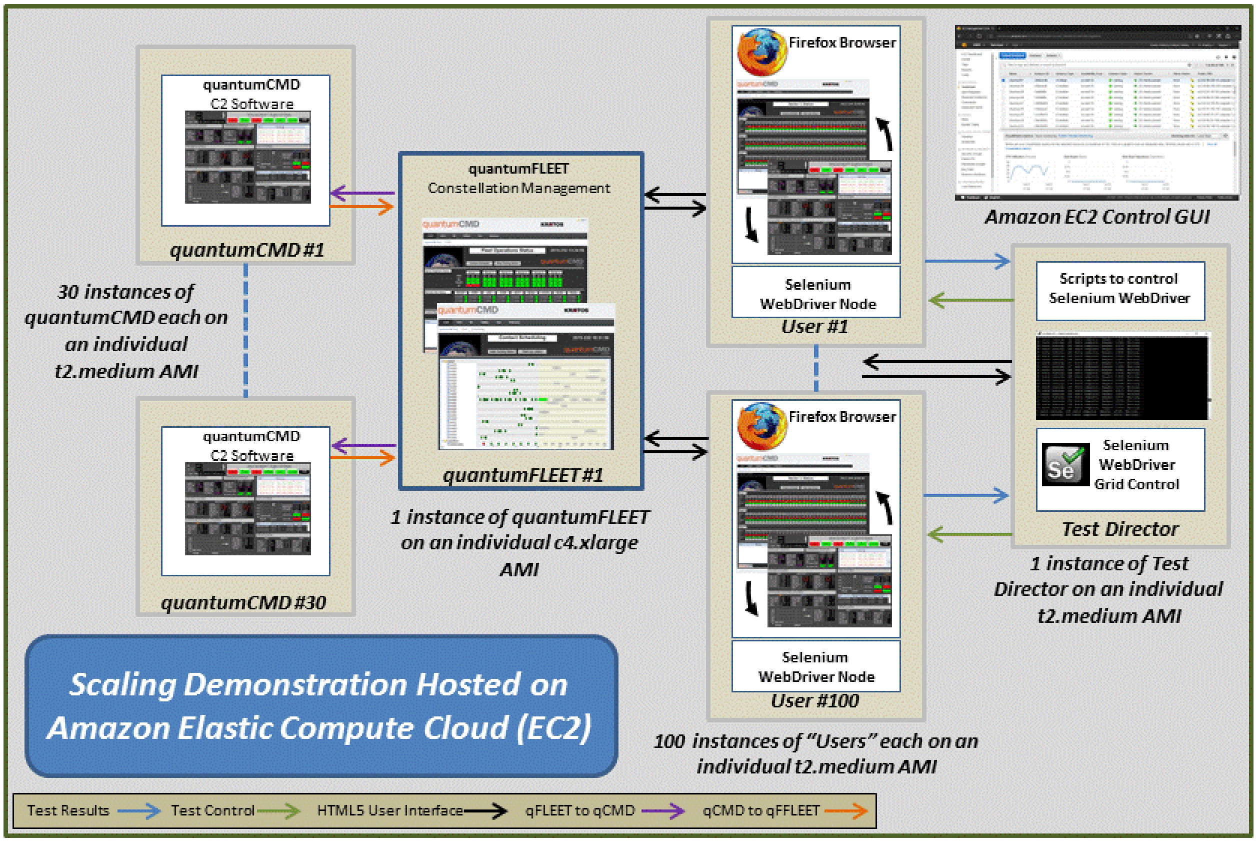

Figure 2 - Kratos used Amazon cloud computing services to simulate the deployment and operations of a large fleet operations center capable of supporting 1,000 spacecraft with 30 simultaneous contacts and 100 users

KRATOS LARGE CONSTELLATION STUDY

Kratos Technology & Training Solutions (Kratos), a division of Kratos Defense & Security Solutions, has decades of experience developing products and delivering end-to-end solutions for satellite ground systems. Years ago, Kratos recognized that the small satellite industry's ground system needs were diverging from traditional satellite missions. The greater emphasis on COTS software, open standards, highly automated operations, virtual machines, and cloud computing led Kratos to develop a new line of satellite ground system applications designed to meet the needs of the small satellite developers and operators. The goal was to introduce a modular ground system solution that was flexible and less expensive than their traditional counterparts. Kratos' quantum product line is a purely software based, pre-integrated solution that is at home when deployed in a virtual machine architecture and employs an HTML5 web based user interface to extend a small satellite operational flexibility.

With the realization that a large scale small satellite constellation was very much becoming a reality, Kratos launched a research initiative to study the feasibility of using cloud services to host a constellation's ground system. The study employed Kratos' small satellite command and control (C2) products, quantumCMD and quantumFLEET. Specifically designed for small satellites, quantumCMD provides central data management of all core command, telemetry and ground Monitor and Control (M&C) needs common to small satellite missions. As an operational management complement to quantumCMD, quantumFLEET is a pure software application designed to meet the situational awareness and management needs of small satellite constellations by coordinating the operations of multiple quantumCMD applications with enterprise-grade functionality.

Kratos selected Amazon Infrastructure as a Service to host virtual instances of the quantum products as depicted in Figure 2 above. The study simulated the deployment and operations of a large fleet operations center supporting a 1,000 small satellite constellation with the capability to manage 30 satellite contacts and 100 users simultaneously. The primary goal of the research was to validate that the quantum products designed to provide C2 capabilities can perform in a full scale environment representative of a large small satellite constellation's mission operations. In order to validate the performance goal, the quantumFLEET instance needed to manage the 30 instances of quantumCMD, which were to operate concurrently, while providing the 100 users with access to their specific satellites contact for operations and/or monitoring of the contact.

Test Parameters

In this test environment all the satellite data as well as the users were simulated. Instead of buying and setting up racks, servers, routers, switches, networks, workstations, etc., Amazon cloud services provided the infrastructure upon which the application's virtual machines were hosted and the network backbone over which all of the users accessed the applications. In a real-time environment, the user would log into the quantum application via a web-based browser to run their satellite contact. Any commands sent from quantum would then be sent out over the cloud's network infrastructure to an antenna site via the Internet to then be radiated up to the spacecraft. Telemetry would work in the reverse with telemetry monitoring being performed on the quantum applications in the cloud and theoretically, the telemetry data could also be stored within the cloud.

The test setup included the instantiation of each of the 1,000 satellites in the constellation, including command and telemetry databases as well as archived telemetry data. Each of the 30 virtual machines established with an instance of quantumCMD included all 1,000 instantiations of the constellation allowing all of the quantumCMD instances to be able to handle any one of the satellite contacts at a given time. A single virtual machine was setup to host the quantumFLEET application, which provided contact scheduling and managed each quantumCMD contact through automation functionality inherent in quantumFLEET. Another 100 virtual machines were established to host each of the simulated user web browsers which controlled by scripts to allow the "users" to maneuver through the quantumFLEET and quantumCMD pages. A final virtual machine hosted the Test Director, which initiated the test scripts and collected test data for subsequent evaluation.

Lessons Learned

Provided that virtual machine characteristics are supported by the cloud service provider, in this case Amazon, virtual machines are easily imported to the cloud environment. This enabled the ability to import production quantumCMD virtual machines quickly rather than having to recreate each instance within the cloud environment, saving numerous man-hours of labor and reducing the risk of introducing errors while recreating those virtual machines.

Through the course of performing the study, a number of observations led to upgrades, which were deployed during the study. The process for deploying these upgrades to the virtual machines within the cloud proved to be identical to the performing an upgrade on a traditional virtual machine.

As expected, the largest performance concern was the single quantumFLEET application, since it maintains connectivity to all of the quantumCMD applications, maintains a wide data set for active and inactive spacecraft, and receives frequent network traffic from user browsers. Amazon, as do most other cloud service providers, offers varying combinations of CPU, memory, storage, and networking capacity that provide the flexibility to choose the appropriate mix of resources for your applications. By running on a more powerful virtual machine instance type Kratos was able to neutralize any performance concerns and maximize the performance of the quantumFLEET application.

As a result of the study, numerous enhancements were identified that are now available in the quantumCMD and quantumFLEET applications. Monitoring up to 30 satellite contacts at a single instance pushes the limits of the amount of detail able to be displayed on a top-level display. The traditional method of drill-down from a top-level display to lower level subsystem displays in order to perform analysis or troubleshooting can prove cumbersome and lessens the operator's situational awareness. A few of the enhancements Kratos made to address these issues include the ability to display out-of-limit data points from a context menu (right-click) for a quick assessment of a satellites state of health, the capability to export data from a strip chart to a downloadable file for offline analysis, and the display of last recorded data point values for better situational awareness.

RECOMMENDATIONS

The research initiative validated that quantum products can work in a full scale environment representative of a large constellation's (up to a 1,000 satellites) full mission operations where a single quantumFLEET application could manage 30 quantumCMD applications operating concurrently, supporting 100 users simultaneously performing operations, and that the system could support the definition of 1,000 satellites while managing the data needs for each of them. Up-front costs for building out just the infrastructure simulated in this demo could theoretically run up over $1M, not to mention the long-term costs of maintaining it. At $0.05 to $0.22 an hour charged by Amazon during this study (and most providers offer flat rate discounts for long-term contracts) the cost difference can be pretty significant not to mention the manpower for maintenance. While this demo explored a specific architecture with a single cloud provider and the concept of operations was fairly simple in only considering the command and control aspect of satellite operations, performing satellite operations within a cloud computing environment would appear to be a very feasible option. The cost of simply building the infrastructure required to support the operations of a large constellation may be enough justify it alone.

Further considerations may focus on concerns with relinquishing control of the infrastructure to an outside entity, ensuring access to applications or data, intellectual or data property rights, and data security. These are all valid concerns but they are neither new concerns nor exclusive to cloud computing. Access to a cloud provider is via the Internet, which of course is provided by ISPs and communication companies. Access would be subject to outages and/or rate increases controlled by external entities. While options such as secondary access may be purchased through alternate means at additional cost or the risk of being able to communicate with ones satellites must be evaluated. Another risk to be considered is where and how data would be stored as the access and intellectual property rights of data stored by a second party continues to be a legal issue. Much of this, however, may be resolved simply with establishing solid legal contracts with a cloud service provider regarding data rights. Finally, security weighs heavily on many satellite operators, especially those supporting government entities as the government continues to be very risk adverse. Securing a traditional ground system to government standards can be difficult enough when the system is maintained internally.

Unfortunately, there are no clear-cut delineations as to whether or not using a cloud service provider is better for certain business models over others. But as with any business endeavor there are always options and taking advantage of the features of a cloud computing service to fly a small satellite constellation is worthy of a cost-benefit analysis. Basic considerations to take into account include the amount of infrastructure required for operations of the constellation, the cost of maintenance of that infrastructure, and the cost of labor to perform the maintenance. Beyond that though are additional items to consider such as the user base for the system or in other words, how many users require access to the ground system whether it be for operations or simply for monitoring purposes and how will they be accessing the system. If there are few users and/or they are all local then using a cloud service may not make as much sense as if the user base is vast and geographically diverse.

Flying a small satellite constellation using a cloud service provider is not limited to the size of the constellation. While a large constellation may find huge cost savings in using a cloud provider, such a mission may have the funding or revenue to incur the cost of self sustained traditional ground system that might be more secure with less concerns over data rights or loss of user. On the flip side, a small constellation which would require much less infrastructure might enjoy the longer term savings of moving to a cloud provider and being able to provide their end users with greater access to their data.

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