

Best Practices for Operations of Satellite Constellations

Joseph Howard* and Dipak Oza, Ph.D.†
Honeywell Technology Solutions Incorporated, Lanham, Maryland 20706

Danford S. Smith**
NASA Goddard Space Flight Center, Greenbelt, MD 20771

This paper presents the best practices used by several commercial and government operators of satellite constellations. These best practices were identified through a series of seminars and discussions held at NASA Goddard Space Flight Center (GSFC). The best practices are arrived through many years of experience and improvements made in the operations procedures and the operational systems with the primary drivers as mission safety and cost effectiveness. This paper discusses the operational aspects associated with how different organizations manage complexities of constellation operations. For the purposes of this paper, satellite constellations are groups of similar spacecraft with more than one spacecraft needed to fully accomplish the constellation's mission.

I. Introduction

In June 2005, Honeywell Technology Solutions Inc. (HTSI), through the Mission Operations and Mission Services (MOMS) contract at the Goddard Space Flight Center (GSFC) of NASA, several commercial and government satellite operators were invited to GSFC/NASA for a series of presentations on the efficient management of large satellite constellations. The primary purpose of these presentations was for GSFC personnel to learn more about the challenges faced by current constellation operators, and to apply these lessons learned to future missions. Many of the lessons may also apply to the consolidation of existing missions into single fleet operations centers.

The best practices were determined based on several factors. For most part, the constellation operators identified needed improvements for optimal performance. In some cases, a group no longer was performing a certain function that the other groups were still doing. A qualitative assessment was made to judge the value of a best practice. No attempts were made to quantify the impact of the best practices identified in this paper.

* Flight Operations Engineer, NASA Goddard Space Flight Center, Greenbelt, MD 20771/Code 420.2

† Senior Program Manager, 7515 Mission Drive, Lanham, MD 20706

** Manager, Goddard Mission Services Evolution Center, NASA Goddard Space Flight Center, Greenbelt, MD 20771/Code 581.0

The presenters covered a common set of topics with varying degrees of depth due to their respective emphasis and application on their constellations. The common set of topics is summarized in section II. Due to the proprietary nature of the commercial business and for competitive reasons, the names of the operators are not identified.

II. Best Practices

A. Defining the Constellation

For this work, the constellation is defined as a group of satellites with a common purpose. A minimum set of satellites were needed to fully achieve mission objectives. The spacecraft are placed in particular configurations in order to accomplish the full mission. Whereas having spares is not critical for meeting mission objectives, they were determined to be beneficial to quickly recover from failures. For most part, the constellation operators developed their own infrastructure, viz., dedicated ground antennas, data routing services and customer support.

Two types of constellations are addressed here: large number of low earth orbiting satellites to cover the globe and groups of geosynchronous satellites. The historical way to get wide area ground coverage was the geosynchronous satellite constellations with high powered ground stations. The more recent constellations are the low earth orbiters which need more satellites to accomplish the same coverage. Each of these constellations has its own benefits and challenges, and yet the operations of the two types have many commonalities.

The following topics are explored from the commonality between different types of satellite operators.

- Defining the Constellation.
- Commonalities.
- Significant Events That Drive Changes.
- Anomaly Identification and Tracking.
- Ground System Resources.
- Individual Vehicle Identification.
- Staff Sizing.
- Equipment Sizing.
- Workload.
- Automation.

B. Commonalities

All the constellations reported here had 24-hour operations. The degree of the capabilities on some shifts varied, but all had at least a minimal staff 24x7. This is due to the real-time nature of the mission. Each constellation's mission is to provide a real-time service. It is imperative to correct for any outage of the service immediately due to the utility needed 24x7 for the constellation service objectives. Whereas other missions, such as the ones that NASA operates have real-time needs, the impact on the user community is significantly different. The utility services provided by the constellations, such as communications services and other national infrastructure needs, are critical for citizenry for emergency communications or hazardous situation warnings.

The need for 24-hour operations is also a financial necessity for the business model of the communications missions. Single outages result in loss of revenue. Multiple outages cause customer dissatisfaction and eventually loss of customers reducing customer base. Once the business gets below the critical mass of customer base the ending of the mission becomes an undesirable reality. The 24 hour operations staff reduces the risk for outages and provides the quickest response to any outages.

It was a deliberate strategy due to mission needs on the part of the constellation owners to build the constellations quickly. This strategy was enabled and implemented by the capability to launch several spacecraft on a variety of launch vehicles. The use of a variety of launch vehicles alleviated the risk and avoided the reliance on a single launch service that may be interrupted or halted for an extended period of time due to a multitude of reasons such as a problem with a particular launch vehicle or a part of its facility. When there is a delay with one launch service, the constellation can still be populated through the use of one of the other available choices. Some of the many choices are shown in Figure 1.

In order to quickly populate the large constellations the spacecraft manufacturers had to design satellites that fit to several different launch vehicle dispensers. They also had to design to the different launch loads and other unique features of the launch services.

A challenge faced by the large constellation operators was to launch multiple satellites with each launch. This requires many design accommodations:

- Each satellite must have a propulsion system. For many stand-alone low earth satellites there is no need for a propulsion system. Often, the satellite orbit achieved by a launch service is sufficient for a long and productive over the life of a mission. Having multiple satellites on a single launch, however, drives the need to a propulsion system in order to separate the assets to their eventual configuration.
- The mechanical structure must stack into several different configurations. Each of these constellations had a different numbers of satellites depending on the launch lift capabilities.

The design of the satellite must accommodate for last minute launch reconfiguration. During the manufacturing phase, it is not known which satellites will be launched together. Some last minute adjustments are needed to differentiate one satellite from another. These include setting frequencies and loading PROMs.

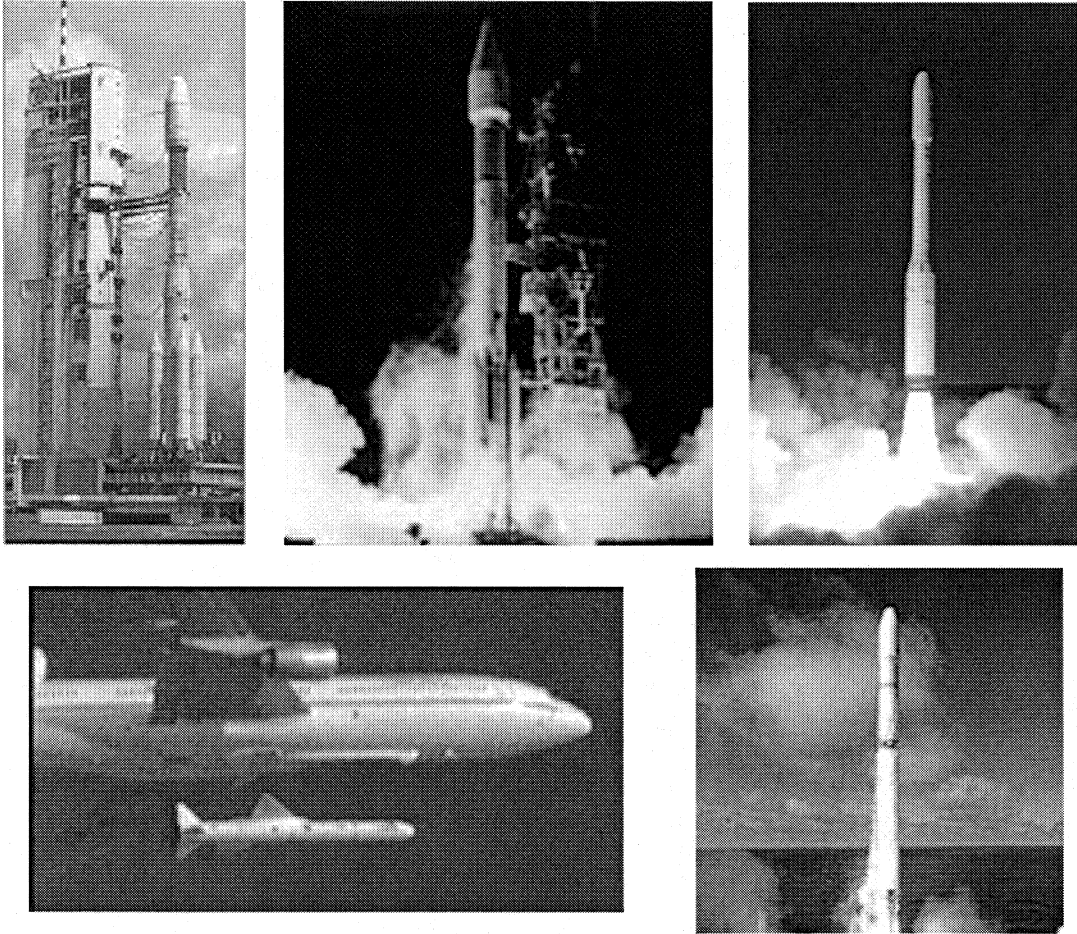


Figure 1. Various Launch Vehicles

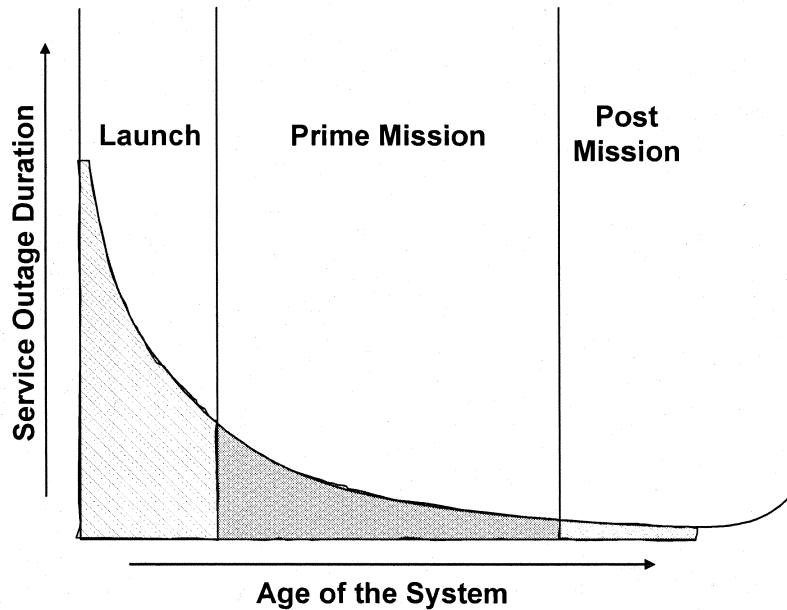
C. Significant Events That Drive Major Changes

It was interesting to note that several of these constellations had significant events that drove dramatic changes toward cost efficiency. Even though a commercial service provider has built-in incentives to be cost effective, it still took a dramatic event such as financial bankruptcy to force bigger changes. Perhaps the biggest change to come forward was to reduce vendor/subcontractor dependence. During bankruptcy, the company is unable to pay for the vendor/subcontractor services. So, they adapted to do without or postponed deliveries. Dependence on in-house development and sustainment of systems was accelerated. Only critical licenses were renewed.

Governmental or regulated services that are privatized also brought most of the support system development and sustainment effort in house. This resulted in cost efficiencies and higher reliability. License fees are a very large expense when the number of systems is multiplied by the number of satellites in a full constellation. Ownership of the systems and software also allows the operations team to select the optimal operating platform.

The one organization that had no change-forcing events had the highest staffing level to spacecraft ratio. This was true for the day time engineering staff as well as the console operators. They also had not automated the remote ground terminals and thus had a large staff associated with each ground station.

All of the constellation missions have seen a change in efficiency when early orbit operations have been completed and the constellation transitions to steady state. This is also valid for stand-alone spacecraft operations. The launch and checkout phase of the spacecraft takes a large team of engineers and operators to perform the checkout activities. Once the checkout phase is complete, the mission begins to focus on the prime mission objectives. The effort is focused on maintaining the primary objectives and quickly resolving any interruptions.



cp1389001.ppt

Figure 2. Change in Efficiency over Time

A contributing factor in the stability of operations is the fact that the infant mortality phase is passed. Most launch-induced or production problems are discovered and remedied. Engineering flaws are also discovered early in the constellation population and checkout phase. Prior to any launches, the I&T team has identified potential problems. The engineers have solved the problems and tested the solutions. Procedures are in place and ready to be used.

D. Anomaly Identification and Tracking

The best practice we found in the area of anomaly identification and tracking across all constellations was to treat each satellite of a given constellation in the same way.

- Display pages contain the same information each vehicle; not a different page for each satellite.
- Summary displays contain critical information of the whole or subset of the constellation.
- One database is established for the whole constellation with processes in place to handle exceptions.

E. Back Orbit Monitoring

The constellation operators deal with back orbit monitoring differently on whether they can use cross links or not. For constellations with cross links capability, as in Figure

3, each satellite is always accessible to the operations team. The operators can continuously scan for problems and correct situations in near real-time. Cross links eliminate the need to review playback data for out of view spacecraft. If crosslinks are not available, the plotting and analysis of back orbit data was stopped after three years for one constellation.

F. Ground System Resources

1. General Network Architecture

All of the constellations had the standard set of hardware and functions:

- planning,
- trending,
- flight dynamics,
- antenna control and
- telemetry and command.

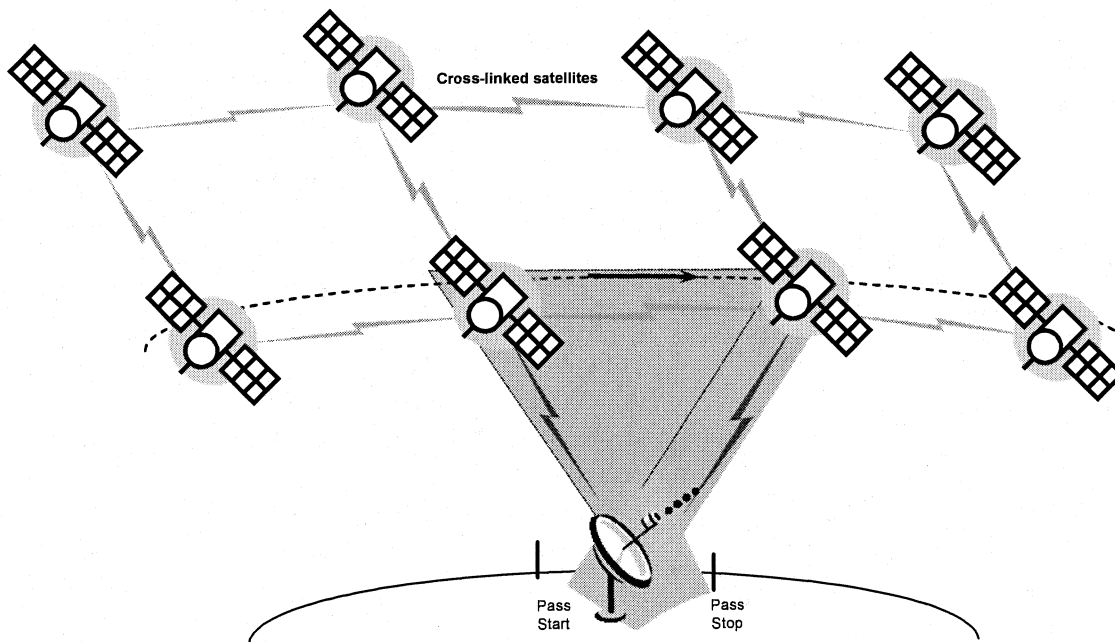


Figure 3. A Representative Cross-linked Constellation

One constellation organization systematically evaluated every function to automate and improve efficiency. It added situational awareness tools and expert systems. It automated failovers. It runs most operations from the planned script. This includes executing maneuvers and ground antenna operations. Executing maneuvers and ground antenna operations are the last two vestiges that are performed and controlled manually by most teams.

2. Command and Control

One constellation team stood out in the command and control system architecture. This organization brought the development effort in house and started to improve and customize all the typical applications. Each function was analyzed and planned for upgrade.

3. Health Evaluation Architectures

All the organizations of the larger constellations quickly evolved summary displays for complete constellation health and status assessments. These typically consisted of color coded boxes arranged purposefully on a page.

Other typical architectures include pop up message boxes for heads-up alerts.

G. Individual Vehicle Identification

The best practice for vehicle ID is to have both orbital slot and vehicle serial number. Both are useful for different applications. One application is for parts tracking. Just as in any mass produced item, it is necessary to be able to identify the lot number. These items are identified and tracked by ground serial number. When the satellite is being manufactured, it may not be known what its orbital slot will be. Other items, such as communications outages and pass planning are best tracked by orbital identifiers.

Some of the constellations communicated with the individual satellites through frequency separation and some on spatial diversity. Others use a crosslink and are able to communicate with any satellite at any time.

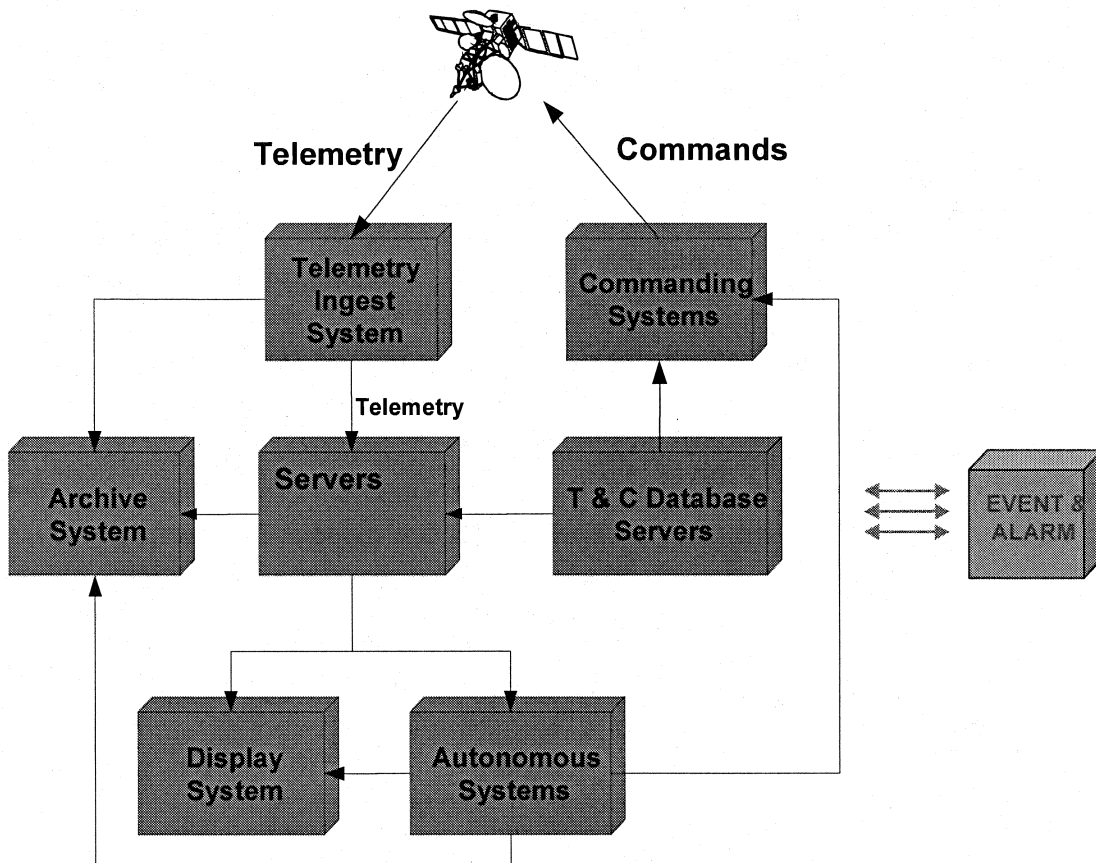


Figure 4. Typical Architecture

H. Staff Sizing

We observed a vast difference in staff sizing across different constellations. A number of factors influence staffing levels.

1. Engineering Staff

This is driven by operations philosophy. Does the organization plan to replace the satellite quickly or are they going to put every effort into maintaining each and every satellite? While none of the organizations were treating the vehicles as disposable, there were significant differences in the approach toward maintenance. One organization had a group of specialized engineers and the capability to modify most of the onboard software. Another organization had an engineering staff mostly composed of only those people necessary to perform normal operations like maneuver planning. It had little capability to modify any onboard software.

The approach is driven by the financial pressures and bankruptcy being common in the market place, the lower cost becomes a primary driver. There was no conclusive data to show that any approach influenced the spacecraft lifetime positively or negatively.

There is a general recognition and some of the organizations have consciously implemented technology to allow reductions in staffing levels. The staffing levels can be reduced further, but it is also recognized that there is a need to keep sufficient staff to maintain spacecraft engineering expertise. This is a cost/risk trade that each organization must balance.

2. Console Staff

3. It was difficult to isolate and measure the level of console staff that each organization was deploying. This is due to the fact that the skill level has migrated and merged with the engineering skills as the automation has been deployed to replace manual operations. Early operations of any system are very manual. Constellations that are large compound the workload. As a result, the console staff level is high at the beginning of the constellation mission. As automation and process improvements are introduced to manage routine operations, the console staff is reduced. It is not unusual that with increased participation in the automation and process improvements, the console operators mature their engineering skills and graduate from console to the engineering support.

I. Equipment Sizing

All the constellation operators expressed the concern over the ability to update ground equipment and software. The common solution is to have a backup control center that can handle operations for enough time to perform any upgrades to the prime facility.

There was a significant difference amongst the constellation operators in how they utilized their back up centers for activities other than normal upgrades. The most efficient use of these resources was the constellation that split payload operations and satellite operations. Each site was prime for either payload or satellite. When the primary satellite control center had a problem, the payload operations center could assume control for a short period of time.

Several organizations maintained backup control facilities within driving distance to the prime sites. These organizations felt that this comfortable distance was a real benefit to them. This is driven by corporate reasons as well as the particular disaster that is being mitigated. This has changed over the years and is also driven by location. For example, an operation in California must plan locations around earthquake fault lines.

The smaller constellations have a dedicated string of command and telemetry equipment for each satellite. They share resources in the planning and analysis areas. They also have common test equipment.

The larger constellations handle multiple satellites with each string. This is where the economies of scale are realized. Most of the systems are handling many satellites at the same time. The expert systems are handling all the satellites and feeding this information to the operators.

J. Workload

All the constellations have introduced automation to reduce the manual workload of each function. However one constellation has taken on more functional responsibilities and kept the staffing level fairly constant. This is a good practice if the business base is growing. But for cost conscious organizations, this is not possible.

The way that each team has been able to reduce the workload is to build automation software that takes over most of the routine activities. The operators and engineers are used mostly to handle the exceptions. And in the case of large constellations, this is not an uncommon event. One constellation counted 15,000 activities per week.

One best practice that we identified was the use of remote monitoring capabilities. This team has set up several laptop computers with encrypted disks. They can get access to the telemetry and other systems through wireless networks and from remote location such as a home. This system allows for the most efficient use of the expertise that is on the team.

As the satellites of the constellation age, the workload is expected to increase due to a number of factors. There is a need for more staff to process changes for handling the older spacecraft. This is compounded by the fact that there will be a need to keep track of many more satellites individually. There are many differences from one satellite to the next. As a result, there are more individual spacecraft specific procedures and software.

K. Automation

The best automation practice is to put the automation on board the spacecraft. Using a GPS reduces the flight dynamics and time correlation tasks to a minimum. They still have to plan orbital adjustments, but, orbit determination is virtually eliminated. When on-board solutions are not practical, deployment of expert systems on the ground are preferred.

In one case, the satellites are susceptible to spontaneous power switching. This problem, multiplied across an entire constellation, takes most of the operators' monitoring and response time. It is also the cause for most of the down time of the service. The response has become very routine for the operators, but the satellites don't have the ability to autonomously perform this response. In this case the automation was performed on the ground with an automated detection and response. A further best practice was to deploy automation processes to use more than one telemetry point to determine the validity of the anomaly before automatically starting the procedure to remedy the problem.

In general most of the constellations have automated and streamlined ground operations to handle the multiplication factor that comes with a constellation. But as new generations of satellites are developed, these ground operations are migrating many functions on board the satellites.

L. Lessons Learned

One organization wished that they had enough simulation capacity to stress all the data sources of a complete constellation. The larger constellations really do have a scale up factor that should have been simulated. More hardware was needed and several operational concerns were satisfied before resolution of this situation was realized.

The initial launch irons out most of the ground software and operations plans. It would be best to have some planned delay between the first launch and the rest of the launch campaign. This time is needed to make updates to systems and mature the ground teams for a more complete constellation.

M. Future Challenges

Most NASA operations teams are used to operate one satellite in one control center. Decisions are usually balanced by the health and status of that one satellite. Some of the longest lived of these are rarely older than 20 years old.

The newer larger constellations knew at the onset of the constellation development that it would be difficult to change ground systems. They made their choices of operating systems and operations software products. However, all the speakers expressed that changing out systems is still a concern. It must be recognized that no matter what is chosen as the latest product, the future cannot be predicted.

The challenge of these constellations for the upcoming years is how to proceed for extended lifetimes. New satellites introduced into the constellation will have new capabilities. Ground computers will need to be replaced. Yet, the constellation will be a mixture of older and newer designs.

III. Conclusion

This paper presented several best practices of constellations.: Some of the recommendations are:

- Eliminate operations tasks on the ground rather than streamline them on the ground. It is more efficient. The use of a GPS is the best example.
- Treat the constellation as a whole.
- Perform ground software updates in house and plan routine refreshes.
- Design for multiple satellites on multiple launch vehicles.
- Have a backup control center at a comfortable distance from prime operations facility.

Finally, each constellation operation is operating in a competitive, global market. Inevitably only the operations that can produce the best product at the best price that will continue to survive. Satellite technology will continue to improve and new generations of satellites will need to be integrated into the older constellations. However, one constellation operator suggested the best practice of all, "Simple really is better."

Acknowledgments

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