SSC97-VII-5

Orbview-1 Autonomous Mission Operations

Abstract. The Orbview-1 spacecraft was launched in April, 1995. It is a small, low-orbiting satellite with two scientific payloads, the Optical Transient Detector (OTD) and the GPS Meteorological instrument (GPS-Met). The Orbview-1 mission was developed in alignment with NASA's directive of "cheaper, better, faster" satellite programs. An important element in achieving these goals is the reduction in operations cost through spacecraft automation. A highly autonomous satellite minimizes the amount of human interaction required once the spacecraft is on-orbit. In alignment with this philosophy, the Orbview-1 Mission Operations have also been increasingly automated. This process has led to reduction of operating costs, scheduling errors and operational errors. It has also resulted in significant improvements in the rate and reliability of data delivery.

This paper will provide descriptions of the Orbview-1 spacecraft and the Orbital Ground Segment which provides Command and Control capabilities for this satellite. It will discuss the progression of the automation of Orbview-1 Mission Operations from inception to the present and the specific improvements in operating costs, data collection and data quality realized from each step. This paper will also suggest additional changes which can be implemented to further automate Orbview-1 Mission Operations and which automation steps can be transferred to future satellite missions.

Introduction

Orbview-1 was successfully launched by Orbital via a Pegasus rocket on April 3, 1995. The Pegasus placed Orbview-1 into a 735 km, circular orbit at an inclination of 70 degrees. After a one week checkout of the subsystems and instruments, the satellite was placed on-line. The bus and instruments were performing nominally.

The OV-1 Operations Plan required that we man five passes per week, one pass a day, Monday through Friday, during business hours, once normal operations commenced. Ideally, the manned passes would consist only of downloading data and uploading stored commands to download data during unmanned passes. Because this workload was anticipated to be relatively light, only one full-time Flight Controller was hired to operate the spacecraft. Engineering staff were available to offer backup support on a part-time basis. The Flight Controller's duties were also expanded to include mission planning, trend analysis, anomaly resolution, and customer liaison.

The first month of operations brought only two operational challenges to light: The primary on-board computer tended to reset and shed the payloads, and the GPS receiver failed to obtain GPS fixes within a particular beta angle range. The lack of GPS fixes, which was due to the placement of the GPS antennas, was compensated for by uploading state vectors from the ground. The Flight Controller became responsible for generating the state vector commands.

We developed a standard recovery procedure to respond to flight computer resets. Unfortunately, the payload shedding which resulted from the flight computer resets led to data losses. The only way to minimize these losses was to man every pass, a change which seemingly called for increasing the number of Flight Controllers. We were able to avoid the cost and complexity of 24 hour staffing, while maintaining a data collection rate of over 90%, by the use of automation.

System Description

The system consists of the spacecraft, the Remote Tracking Site at Fairmont, WV, the Control Center at Dulles, VA and the two Orbview-1 customers, Marshall Space Flight Center (MSFC) and University of Colorado Atmospheric Research (UCAR). MSFC designed and built the OTD instrument and

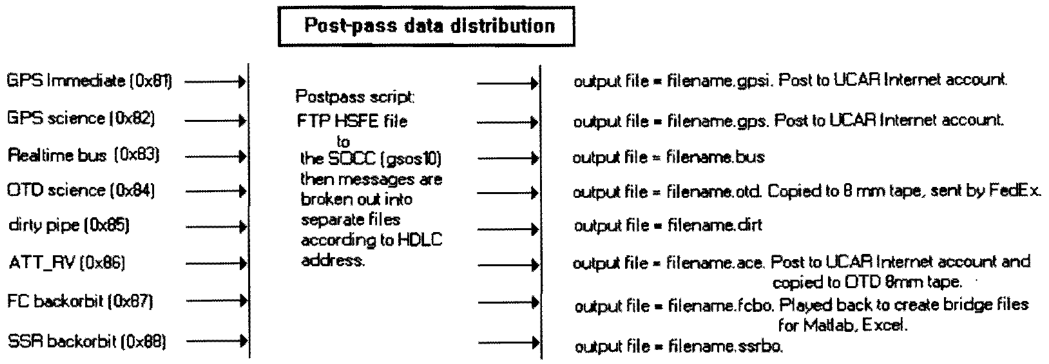

Figure 1. Data distribution scheme for Orbview-1

directs its operation. UCAR directs the operation of the GPS-Met which is a product of the Jet Propulsion Laboratory.

The satellite's orbit allows four to six passes over the Fairmont tracking site per day. The maximum pass duration is roughly 15 minutes. Nominally, two of those passes are taken each day. During a pass, stored commands and instrument commands are uploaded to the spacecraft. Real-time telemetry, backorbit data and all science data are downloaded to the Fairmont site. All data output from the data receivers is recorded on analog tape. Once through the receivers, the data is passed to bit synchronizers and the digital stream is forwarded to one or more high speed front ends which, in turn, log all data to disk. The high speed front ends are SUN PC computers running the UNIX Interactive Operating System. Separate cards handle Orbview-1's downlink data rates of 2 Mbps (normal) and 57.6 kbps (contingency).

Of the 14 passes taken each week, five are manned. During these passes, the high speed front ends are configured to pass real-time state of health telemetry and command responses to the Dulles Command and Control computers. The high speed front end software examines each incoming HDLC message wrapper in order to ascertain that message's source. Three of the eight spacecraft data sources are treated as real-time data, and are forwarded.

The Command and Control computers are SUN Sparc 20 machines running the UNIX Solaris Operating System. The first computer to receive incoming data is the Data Server. Its task is to unwrap each message, retrieve its individual telemetry points and forward them, along with the message time-tag, to Clients, upon request. The Clients, which reside on the second Command and Control Computer, are the Commander and various monitoring tools, such as graphs and telemetry pages. Only a small subset of points is directly observed via the telemetry pages and other Clients, so a limit checking tool was developed which requests all available points, so that no point is unmonitored.

Post-pass, the high speed front end logfile is copied to the second Command and Control Computer. The logfile is sorted into subfiles based on data type. The sorting program uses the same portion of the message wrapper that the high speed front end does to recognize the spacecraft data source. The post-processing script then acts on each file, forwarding it to its final destination as customer or archived data.

Space Segment Description

Orbview-1 is a 68 kg spacecraft. Its structure consists of a disc-shaped component compartment, two deployable, rotating solar array paddles, and a telescoping boom which extends to 15 feet.

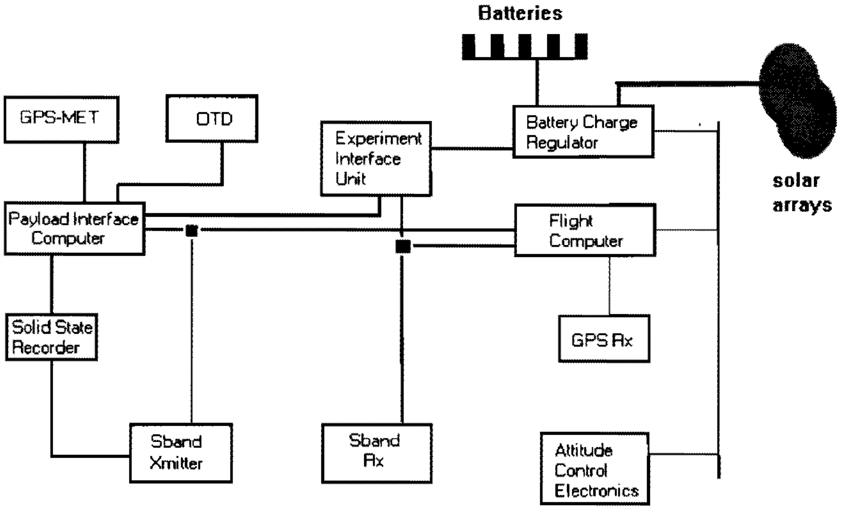

Figure 2. Orbview-1 Top Level Diagram

The Orbview-1 spacecraft is designed to operate autonomously. Its subsystems are based on four microprocessors. Attitude Determination and Control software is contained within the Attitude Control Electronics processor. Power, Thermal, and switching software are resident on the Battery Charge Regulator processor. Command Handling, Telemetry Gathering, Communications, and processor monitoring tasks are part of the Flight Computer software. Payload handling, which includes forwarding instrument commands, receiving instrument telemetry, and storing science data, is done by the Payload Interface Computer.

Unit switching is performed via the Experiment Interface Unit. The Experiment Interface Unit also provides power conversion from the 14 Volt main bus to the 5 and 28 Volt buses. Figure 2 provides an overview of Orbview-1.

Attitude Control Subsystem

The attitude and orbit of the spacecraft are determined on board. A GPS Receiver tracks GPS satellites and forwards GPS fixes to the Attitude Control Electronics. The Attitude Control Electronics combines this with sensor information and propagates the spacecraft orbit based on this input. If necessary, state vectors can also be loaded directly from the ground. From this orbit estimate, the Attitude Control Electronics calculates its ideal attitude with respect to the Earth and it calculates the approximate pointing for the solar arrays. The Attitude Control Electronics utilizes inputs from horizon sensors and from a magnetometer, which is mounted on the boom, to estimate the spacecraft's actual attitude.

The attitude control is primarily gravity gradient; additional control is available via two perpendicularly arranged magnetic torquer rods plus a third air-core torquer which encircles the interior of the compartment. The torquers are driven by the Attitude Control Electronics to align the spacecraft estimated attitude with the ideal.

Figure 3 shows how the Attitude Control Electronics interfaces with other bus units. The Experiment Interface Unit provides regulated power to the Attitude Control Electronics, the GPS Receiver, attitude sensors and actuators. The Flight Computer forwards GPS Receiver data to the Attitude Control Electronics. The Battery Charge Regulator accepts solar array pointing commands from the Attitude Control Electronics.

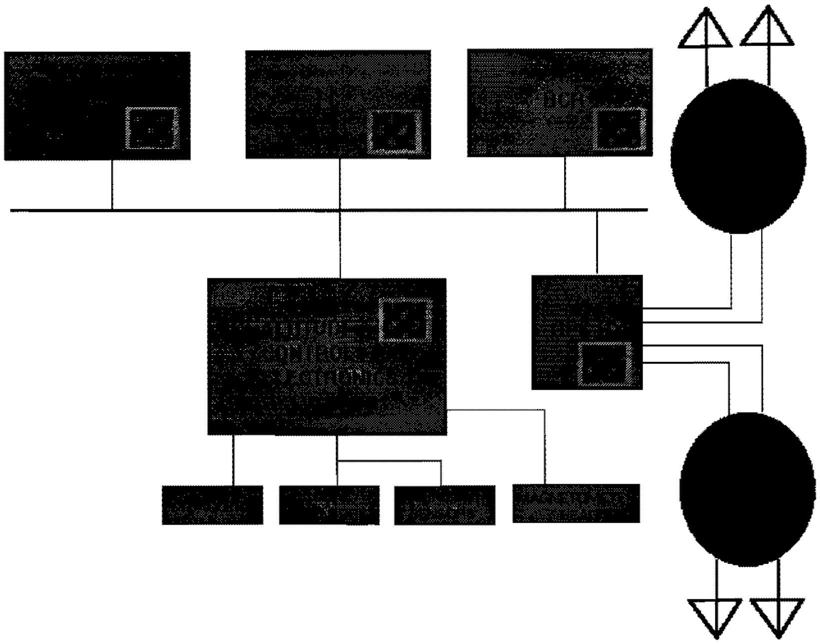

Figure 3. Attitude Control Subsystem Overview

Power and Thermal Subsystems

As shown in Figure 4, the units which comprise the Power and Thermal Subsystems are: The Battery Charge Regulator, two solar array paddles, five battery cells, and four heaters. The Battery Charge Regulator monitors and controls temperatures for the boom hinge (only active during deployment), the battery cells, the solar array drive and the OTD instrument. The Battery Charge Regulator also receives solar array commands from the Attitude Control Subsystem. Those commands are supplemented by the Battery Charge Regulator; the arrays are dithered about the Attitude Control Subsystem commanded position to locate the array angle which provides maximum power. The Battery Charge Regulator monitors battery state of charge and controls battery charge rates. It also sends switching commands to the Experiment Interface Unit to shed non-critical loads in the event of low power.

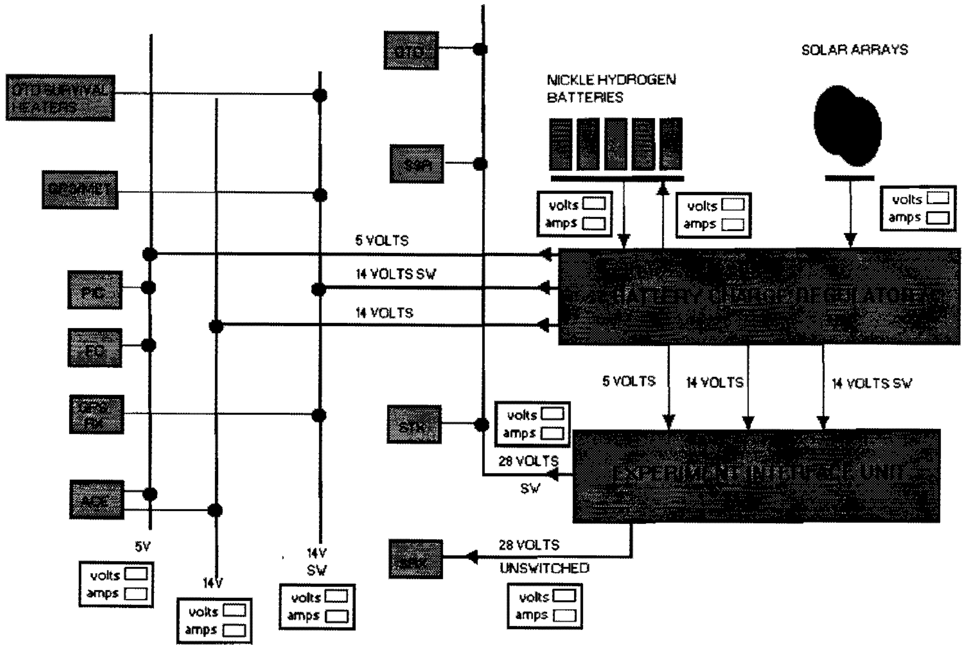

Figure 4. The Power and Thermal Subsystems

Payloads

Orbview-1 carries two scientific instruments, the Optical Transient Detector (OTD) and the GPS Meteorological instrument (GPS-Met). The OTD Program is run from Marshall Space Flight Center in Huntsville, Alabama. The instrument is designed to detect cloud-to-cloud lightening in darkness and in daylight.

The GPS-Met calculates atmospheric moisture density. It tracks GPS satellites, locks to those signals, then records and processes the attenuation of those signals as each GPS satellite orbits behind the Earth relative to Orbview-1. In this configuration, the signals from the GPS satellite travel through the Earth's atmosphere en route to the GPS-Met instrument. The signal variations measured by GPS-Met are a function of atmospheric moisture density.

Commands and telemetry for both instruments are routed via the Payload Interface Computer. This processor also retrieves all science data and stores it on the Solid State Recorder for eventual download over the Orbital Ground Station.

Communications

Uplink

Commands are received via an S-band Receiver at the rate of 19.2 kbps. All commands are routed to the Flight Computer which stores time-tagged commands and forwards immediate commands to the appropriate on-board task. The task, in turn, routes its command response back to the Flight Computer. The Flight Computer wraps the command response as a telemetry message and forwards it to the ground.

The Flight Computer is capable of handling single commands, stored commands or software uploads.

Downlink

Orbview-1 utilizes a packetized telemetry scheme. The Flight Computer retrieves telemetry messages from various tasks based on a Telemetry Table within the Flight Computer. The Telemetry Table identifies which packets are to be retrieved from which tasks and at what rate. The Flight Computer collects and forwards high rate bus telemetry at all times. It also collects and stores low rate bus

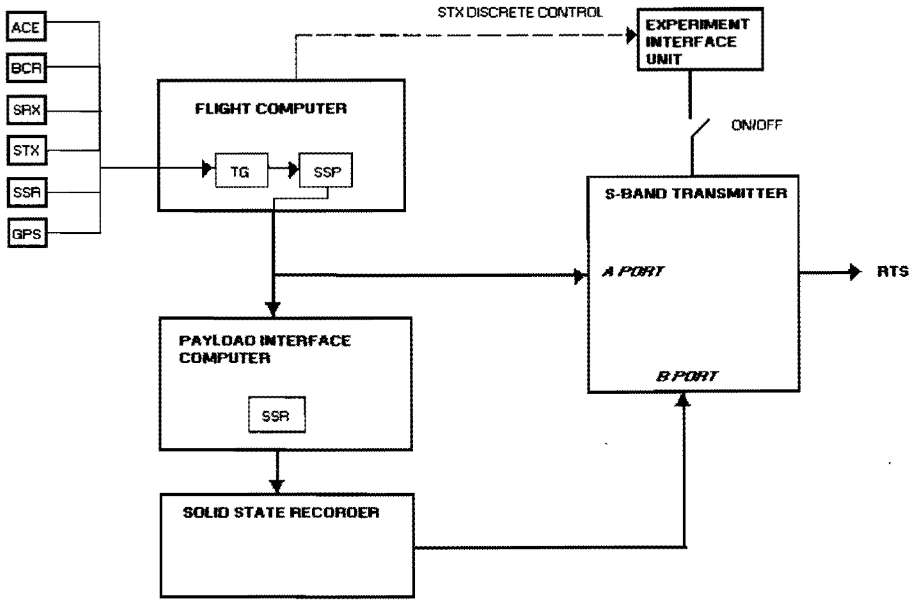

Figure 5. The Downlink portion of the Communications Subsystem

telemetry as backorbit data which can be downloaded via ground command. High rate and low rate telemetry are forwarded from the Flight Computer to the Payload Interface Computer.

In normal downlink mode, the Payload Interface Computer accepts all bus data from the Flight Computer and forwards it to a specific partition in the Solid State Recorder. The data in this partition is forwarded to the downlink transmitter almost immediately. This takes place whether the transmitter is on or off. If science data is also being downloaded (via ground command) the Solid State Recorder is commanded by the Payload Interface Computer to download portions of each partition in turn, cycling through until all partitions have been completely read. The bus data partition is included in this process. The downlink data rate for all Solid State Recorder data is 2 Mbps.

A contingency data path is also available. The communications link between the Flight Computer and the Payload Interface Computer is teed to a second port on the downlink transmitter. This route allows bus data (high rate and low rate) to be forwarded to the ground at a 57.6 kbps rate. Switching from normal to contingency rate is the equivalent of switching from the primary to the secondary transmitter port.

Ground Segment Description

Orbview-1 Commanding, monitoring and science data collection are all performed via the Orbital Remote Tracking Site in Fairmont, West Virginia. The site equipment consists of a single 10 meter dish which can be driven in Autotrack, Program Track or Horizon Scan modes.

Commands and software uploads generated at the Dulles Satellite Control Center are forwarded across a T1 communications line to an uplink high speed front end at the Fairmont site. The command packets are formatted into a serial bit stream by the high speed front end. The bit stream is then passed to an amplifier. Its output, in turn, modulates the uplink carrier.

The downlinked spacecraft data is demodulated and bit synchronized, then forwarded to a high

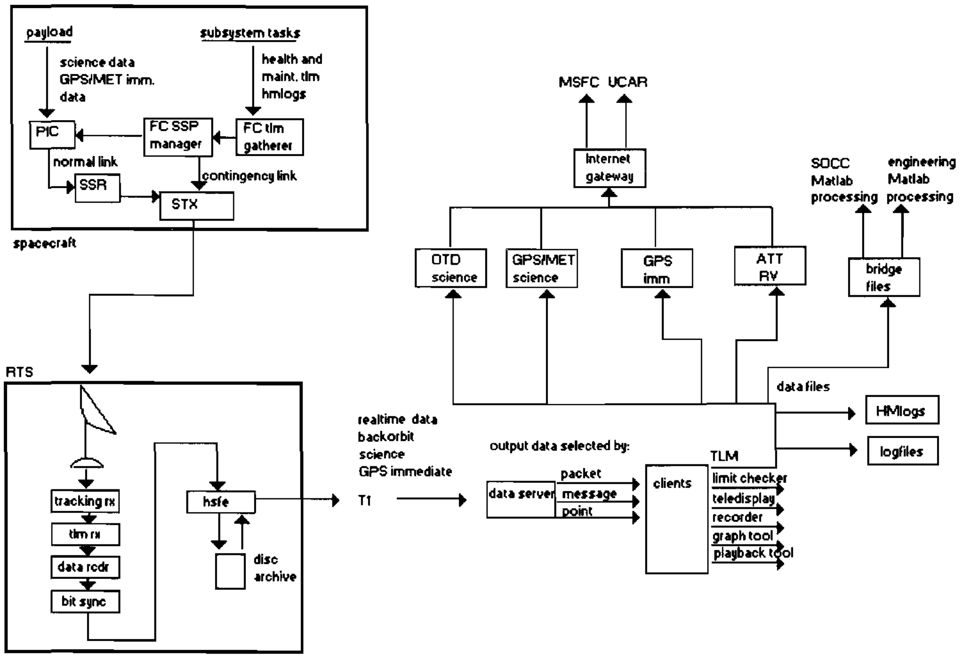

Figure 6. The Ground Segment System Overview

speed front end processor (hsfe). The hsfe captures and logs all data to disc. Upon request, it also forwards selected data (spacecraft state of health telemetry and command responses) to a Data Server at the Dulles Satellite Control Center. The Data Server unwraps the telemetry packets received from the hsfe and provides telemetry points to Clients which request them.

Once a pass is completed, the Flight Controller runs a script which halts the software on the hsfe, the Data Server and the Client host (the on-line computer). Once shutdown is complete, a second script is run to perform logfile processing. The logfile on the hsfe, which contains all data received from the spacecraft, is copied to a local directory on the Dulles Satellite Control Center on-line computer. The logfile is then processed by breaking out the various data types (backorbit data, OTD science data, GPS-Met science data, and state-of-health data) into separate files. All files relating to spacecraft state-of-health are archived to disc and, eventually, to CD ROM. All customer files are posted to the Dulles Satellite Control Center Internet Server where they can be retrieved by the customers at will. Finally, the local copy of the intact logfile is compressed and saved on 8mm tape for permanent archive.

A variety of tools are available to retrieve state of health files from archive in order to perform trend analysis and anomaly resolution tasks. Files can be individually processed into Matlab format; we've written an extensive number of Matlab scripts which generate standard data plots. MAESTRO, an Orbital software package which can be utilized for Spacecraft Integration and Test or On-Orbit Operations, also provides playback tools for data analysis, including telemetry pages, graphs and tables. The flexibility of the MAESTRO playback function makes it an ideal tool for anomaly resolution. We have recently begun to develop MAESTRO scripts which mirror the MATLAB plotting scripts. This will soon lead to MAESTRO being our primary analysis tool.

Automated Operations

Orbview Operations have been kept simple. A single startup script initializes the uplink and downlink hsfe software, the Data Server and all required Clients. A second script performs the software shutdown at the end-of-pass and a third script does all the postprocessing and data distribution, including the posting of science data to the Internet Server. This simplicity paved the way for automating operations.

On Friday of each week, a pass schedule is generated for the next week. The pass schedule is formatted for Excel so that it can be opened as a spreadsheet. Once this is completed, an Excel Macro is run against the pass schedule. The Macro generates some additional information for each pass such as Pass ID, day of the week and UTC day. The Macro then calls a variety of functions and sub-macros to select which passes to track each day and which passes must be manned. Based on this information, the Macro generates a filtered schedule for customers, as well as generating the week's pass plans. The Macro takes seasonal conditions into account (certain commands are uploaded in accordance with particular orbital beta angles) as well as all standing instructions from customers.

Standard command scripts reside on the on-line operations computer. Updates to command scripts, such as new time-tags, are entered manually in order to provide an opportunity for the Planner to check the validity of the pass schedule and pass plans. We've applied rules to assigning time-tags so that updates are routine. We can update the time-tags for a standard load in about 30 seconds.

Controllers also schedule the remote antenna to track all applicable passes for the upcoming week via the RTS control software. In all, the Mission Planning for Orbview-1 requires approximately one hour per week, including checks. This is less than one-fourth the time required prior to automating Mission Planning.

Fewer than half of Orbview-1 passes are manned. Our original Operations Plan called for stored commands on Orbview-1 to switch on the downlink transmitter, and download all recorded data, during unmanned passes. This data would be captured at the Remote Tracking Site on analog tape, then played back the next business day. After playback, it would be processed and distributed. Because of Internet access restrictions, our primary customer at Marshall Space Flight Center initially received OTD science data on 8mm tape via courier. The minimum delay between collection of science data at the Remote Tracking Site and its arrival at MSFC, was 24 hours. The maximum delay (over weekends) was as much as five days.

Piece by piece, this entire process was automated. With this automation came increased speed and reliability of data distribution. The first transition was from collecting data on analog tape to collecting data directly onto a downlink high speed front end which was controlled via time-tagged script. (The analog tape continued to provide backup data collection.) The next step was to time-tag the postprocessing script so that it would begin just at the end of a scheduled pass. The script was also updated so that the science data processed for UCAR was automatically posted to the Internet Server.

One of the most significant steps taken in automating the Orbview-1 operation was to incorporate a monitor/paging system. All computers associated with spacecraft operations at the Dulles site and at the Remote Tracking Site were placed on a monitoring system. At this time, if any one of these computers fails to respond to an aliveness test, one or more of our staff (depending on which computer fails) is paged. The pagers we use are alphanumeric so that the system can report which computer is off-line.

We soon added a task to the monitoring system. The postpass processing script was updated so that the logfile size would be examined after the logfile was copied to the Dulles Satellite Control Center. Now, if a filesize is smaller than expected, the script forwards a message to the monitoring system to page the Controller. Since all passes are scheduled such that a follow-up pass is available, this allows the on-call Controller to respond to the page by manning the follow-up pass. This upgrade has improved data collection by over 15% without significantly increasing costs or manning. Data collection from Orbview-1's first quarter of operations was approximately 75% of the total possible. The next three quarters, the collection rate averaged 85%. After the addition of the paging/monitoring system, collection improved again, to over 90%. Throughout the mission, staffing has remained at only one full-time Flight Controller.

This particular upgrade was effective because our primary cause of data loss is Orbview-1 flight computer resets. A flight computer reset forces the Payload Interface Computer and both payloads to power off. Also, all stored commands are deleted from the Command Handler stack, so that once a reset occurs, no more data is collected and any data which is still on the recorder is not downloaded unless a Controller intervenes. For this reason, prior to the logfile size detection and notification system, a flight computer reset could occur sometime after a manned pass, halting science data collection. The next pass would normally be unmanned, so the problem would go undetected. This resulted in data losses of up to 24 hours for resets taking place during the week, or three days of data loss, if over a weekend.

After the logfile detection/notification system was in place, a flight computer reset was detected during the next pass, manned or unmanned. For an unmanned pass, the on-call Controller would receive the page informing him of the zero-length logfile, and he would have time to get to the Control Center, take the follow-up pass, and recover the spacecraft. Data loss due to a flight computer reset dropped from a maximum of three days to a maximum of about 14 hours. Most losses are less.

Another problem we encountered was low data quality; the antenna at the Remote Tracking Site was intermittently losing track over elevations of 65 degrees. Our study revealed two problems: Orbview-1's antenna pattern is flawed such that the downlink signal decreases below the ground antenna's tracking threshold at particular spacecraft-to-ground-antenna look angles. The second problem was that the ground antenna software was designed so that any loss of track switched the antenna mode into Acquire. The dish would start to spiral immediately. Had the antenna switched into Program Track, the loss of signal would have only been a few seconds. Instead, relocking to the spacecraft signal often required one or two minutes; since the science download is only six minutes long, much of the download was either corrupted or lost in this circumstance.

Dropping the threshold enough to maintain lock also lowered it enough to allow the antenna to lock to the signal's sidelobes, so this was not an acceptable option. The workaround we initially adopted was to select passes with a peak elevation below 60 degrees and, if a higher elevation pass was required, perform the download very early in the pass. The early downloads often led to noisy data due to interference from ground site obscura, so the situation remained unsatisfactory.

A better solution was, once again, derived from automation. This time, the customers made the changes. Sort programs were included in their software such that incoming data was sorted into the existing data set. This allowed us to download data on successive passes, forward all data to our customers, and let their software extract the optimal data set. Packets which contained noisy or duplicate data were simply discarded.

This problem has been further addressed by continuing to make improvements in ground antenna performance. Loss of track on high elevation passes has been remedied. The antenna mode no longer switches into Acquire in response to Orbview-1's brief dropouts. Overall, the typical number of bad CRCs due to ground problems has decreased from several hundred per pass set to near zero.

Our most recent improvement takes advantage of two Internet related upgrades. The Dulles Satellite Control Center now has its own Internet Server so that the large science files can remain on the Server without occupying a disproportionate amount of storage. In addition, the access line has been upgraded to a full T1 so that the transfer of these files does not significantly impact other users. Because of these changes, we were able to begin posting OTD science data to the Internet as well as the GPS-Met science data. The minimum delay between collection of science data at the Remote Tracking Site and distribution to MSFC dropped from 24 hours to less than half an hour. Moreover, this small delay is consistent whether the pass occurs mid-week during business hours, or during an unmanned pass during a holiday break.

Both customers retrieve and process their respective science files automatically, as well. This overall automation is so rapid that, if Internet traffic allows, it is possible for a customer to retrieve and process data quickly enough to forward instrument command instructions to us in time for the follow up pass 100 minutes later. (Fortunately, this is a rare requirement.) This increase in the rate of customer feedback has enabled us to continue to reduce the period from the start of a satellite or ground segment problem to its resolution. As automation continues to close the feedback loop between Orbital and our customers it is clear that all improvements have led to faster, more reliable service while maintaining low operating costs. This process has also resulted in our customers and ourselves developing into a team, which may be the most significant benefit of all.

Because automation of Mission Operations has been so beneficial, we're continuing to search for further applications. One powerful tool would be to monitor specific telemetry points, such as Battery State of Charge, and page the on-call Flight Controller for out-of-limits conditions. The sophistication of the system could be increased by adding an intermediate program which would monitor a series of ground segment and spacecraft telemetry points, and provide a first analysis of a system problem. The result would be forwarded to the staff via pager.

This level of automation, including logfile size examination, prompt processing and forwarding of customer data, and preliminary analysis of system health, could be transferred to future programs with a minimum of effort. Applying automation to future programs is reasonable, even if the program is fully staffed for 24 hour operations. It's evident that automation supports small staff strategies. But even well-staffed programs can benefit, in that automation reduces errors.

Conclusion

Mission Operations can be simply designed. When overcomplexity is avoided, automation of Mission Operations can be adopted smoothly, by integrating non-automated tasks piecewise into the process. Increasing automation of Mission Operations has reduced our operational costs and errors, increased our quantity of data collected, led to improvements in data quality, and decreased response time to anomalies. Continued application of automation to Mission Operations can potentially lead to faster anomaly resolution, as well. All of these benefits can be inherited by future programs, decreasing the overall costs and increasing the overall quality of spacecraft operations.