Optimizing Satellite, Network, And Ground Station Operations With Next Generation Data Visualization[1]

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Abstract— With the ever increasing size and complexity of constellations and ground station networks, monitoring and control continues to challenge satellite operators. Traditional monitoring tools, originally designed for single-satellite or small network operations, do not scale sufficiently well to accommodate increasingly large amounts of data. An entirely new approach to data monitoring is required.

The solution to this problem is not to add staff, but to take advantage of new 3-D visual monitoring technology that provides instant access to alarm distributions and severities. This technology employs limit alarms, trend alarms, count alarms, and alarms set on derived parameters to alert the operator to problems before they happen. The environment is fully visual and can accommodate single-click access to over 100,000 parameters in a single display.

Visual data monitoring gives the operations team a qualitative high-level view of the entire constellation, ground station network, and/or individual satellites or ground stations. The management and engineering staff can also monitor data remotely, giving them a direct interface to the satellite operations center from any location. In addition to reducing staffing requirements, remote monitoring supports lights out operations because it allows engineering and operations personnel to receive alarm notification via pager or email. The training requirements for visual monitoring are minimal; in fact, most users can be trained in less than one day.

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INTRODUCTION

During the last 30 years, the satellite industry has grown tremendously. To keep pace with that growth, satellite operators have made significant improvements to their ground systems monitoring and communications systems. In the future, they will need even more efficient and cost-effective ways to monitor and control their constellations. One technology innovation that allows them to be more successful is *visual data monitoring*.

In the 1970s, satellite operators only monitored and controlled one or two satellites. To control their spacecraft, they used primary and backup Telemetry Tracking and Command (TT&C) facilities, which required around the clock operational support. Operations personnel used a combination of ASCII text-based displays and manually created command lists to perform everyday monitoring and control tasks, and they used manually generated graphs to analyze key telemetry parameters. While sufficient for operating one or two satellites, these tools required large operations teams, and they proved inadequate when operators began launching additional satellites. The fact that the new satellites were more complex and presented larger quantities of data only exacerbated the problem.

The 1980s and 1990s saw continued growth in constellation size as a result of heightened worldwide demand for communications technology. Two additional factors also helped drive up the number and size of satellite constellations: the increasing need for communications in the Pacific Rim, and the formation of LEO-based organizations such as Globalstar and Iridium. (LEO, or low Earth orbit, systems require more satellites to provide continuous worldwide coverage.)

In response to new demands from commercial applications, satellite manufacturers and operators have continued to upgrade their hardware, developing more powerful transponders, larger buses, and more complex payloads, and adding telemetry points. In the early 1980s, companies began to write custom programs for monitoring and analyzing satellite data. They added elaborate tabular displays to the strip chart displays that had been used previously, and created more sophisticated methods of retrieving and reporting anomalous data. Even with the use of so-called "commercial off-the-shelf" software toolkits, these types of enhancements allow an operator to monitor no more than six satellites, and four or more computer workstations are typically required to support the increased load. Furthermore, because the custom software is designed on a satellite-by-satellite basis, it requires a significant investment of software development and maintenance resources.

Constellation size continued to increase in the late 1990s. It is not uncommon for companies to fly 14 or 15 satellites, and the LEO constellations of Iridium and Globalstar contain 66 and

48 satellites, respectively. Teledesic's global, broadband Internet-in-the-Sky will include 288 satellites plus spares in its constellation of LEO satellites. The new MEO (medium Earth orbit) satellites are expected to be launched in the next few years. They will be positioned 9,000 to 20,000 kilometers above the Earth, and will be used for worldwide broadband services, including Internet, e-mail, and video conferencing. Some large operators are preparing to include GEOs (geosynchronous Earth orbit satellites), LEOs, and MEOs in their constellations. These heterogeneous constellations will require the satellite operator to address the unique monitoring and control requirements for each type of satellite in its fleet.

The growth in satellite numbers has brought about a predictable increase in workload. Operators have addressed their staffing shortages by hiring more analysts and controllers or by requiring their existing staff to monitor more satellites. Not surprisingly, the cost of personnel has become one of the largest ongoing investments in the satellite industry.

In order to remain commercially viable, more cost-effective ways of doing business are required across the board. One important area for reducing costs is operations. A new generation of monitoring technology called *visual data monitoring* eliminates the need for in-house software development and maintenance. The software, which works seamlessly with existing satellite control systems, can be integrated in just a few days, and the tools are totally configurable by the engineer or satellite controller even at run-time.

Visual data monitoring provides a single platform for all of a satellite operator's monitoring needs. Displays for routine operations such as eclipse, battery reconditioning, and maneuvers can be built and stored in advance. These displays can be built in a fraction of the time it takes to build conventional displays, and operators can generate emergency displays on the fly, in real-time. Visual data monitoring can also be applied to mixed constellations consisting of GEO, MEO, and LEO satellites.

This cost effective approach to satellite monitoring and control offers a turn-key solution that addresses a host of challenges facing satellite operators. Visual data monitoring significantly reduces staffing and training requirements while lessening the data monitoring burden. And by permitting home access and remote alarm notification, it gives satellite operators the ability to run unmanned remote stations and lights out operations.

Why The Use Of Decade-Old Operations Technology Poses Problems In The New Millennium

Other industries focused their planning for the new millennium on assuring that the time formats in their software accommodated four-digit years. The commercial space industry was equally zealous in its Y2K preparedness, but it has not yet looked at the more far-reaching technological implications of the new millennium. The changes in our industry during the last decade were so extensive that merely accommodating a four-digit year does not go far enough. We must strive to become "Y2K compliant" in the broadest sense, by examining the ways in which we do business and asking whether our tools offer the functionality that will allow us to meet the challenges of the new century.

Operators responsible for complex networks of ground stations or large numbers of potentially diverse satellites are finding that the once-acceptable traditional monitoring and analysis tools developed to accommodate the operations needs of the 80s and 90s are inefficient and inadequate. The most problematic areas relate to data access and presentation, and stem from the fact that a single analyst is only capable of absorbing a finite quantity of data.

Many monitoring systems use complex display hierarchies that reflect the inherent hierarchy of the satellite itself, organizing data by subsystems and then further subdividing it along components within the subsystem. When an alarm in a subsystem is triggered, the color of the icon (or label) that represents the subsystem in the graphical user interface changes from green to red. Clicking the icon reveals more icons, at least one of which will also be red. Continuing to click the red icons eventually leads to the out-of-limit data point. Furthermore, the set of graphs or tabular displays that an analyst can view when traversing a hierarchy is pre-defined by the software. Unless the software is modified, the analyst cannot invoke a subset of those displays, nor can he open displays that are usually viewed in other contexts. The programming required to make these changes often takes weeks or even months to complete, making it impossible to request new combinations of data in an acceptable time-frame. Consequently, this type of system is costly to develop and even more costly to maintain and support.

Data hierarchies are a data presentation solution that originated almost two decades ago, motivated by a desire to give operators a means for organizing the data overload created by the gradual increase in telemetry. As a work-around solution, hierarchies were adequate for the initial increases in data, but they do not offer a scalable solution. This is because hierarchies never actually solved the problem of data overload, they merely created a scheme for imposing order on the problem.

As the industry moved from small numbers of satellites to larger constellations and from hundreds of telemetry points per satellite to thousands, the complexity of display hierarchies grew in direct proportion to the increase in data. Providers of commercial monitoring tools and monitoring systems have gone so far as to require separate workstations for each satellite because display hierarchies no longer effectively support the operation of constellations. One well-known satellite operator with a twelve-satellite constellation actually has twelve "dual-headed" workstations (each workstation has two monitors attached for display of data). Clearly, this is not a cost-effective or reasonable alternative; it is one that arises as a result of forcing yesterday's technology to fit today's operations.

Similarly, operators that manage remote facilities have limited ability to gather and view all of the data from their various facilities, and they have limited means of monitoring their critical data on one centralized display. In fact, even though ground station operators collect and archive massive quantities of ground station data, it is not unusual for them to be unaware of serious operational problems (including customer outages) until they are notified by the customer. This is a direct result of using inadequate tools to present the data that has been meticulously collected.

Finally, most monitoring systems don't have the capability to make data available to analysts who are off site. Typically, the analyst is contacted by phone and the problem is described to him verbally; the analyst then has to make a decision based on experience and gut feeling rather than on the actual data. The other option, and one that is frequently employed when a company is performing a critical operation such as an eclipse, is to bring the analyst in during off hours so that he is present when the eclipse occurs. This alternative allows the analyst to view the actual data in real time, but it is costly in terms of work force expenditures.

The limitations of traditional monitoring and analysis techniques are not insurmountable, provided the analyst has experience with the satellites he is monitoring and has developed workarounds to deal with the shortcomings of the technology. Such "experience workarounds" can be sufficient when the operator is only monitoring a few satellites. However, these limitations are a serious impediment for any operator that wants to expand its constellation without adding staff or increasing risk.

VISUAL DATA MONITORING AND ANALYSIS

All of the technology shortcomings described thus far can be eliminated with visual data monitoring. This technology consolidates massive amounts of real-time data and presents it in a unified 3-D environment that can monitor several hundred thousand parameters on one system and can comfortably accommodate single-click access to 100,000 or more data parameters in one view, at one time (see Figure 1).

This display, called the "CyberGrid," offers a complete departure from conventional monitoring technology – one that is required to deal with the several-orders-of-magnitude increase in data, on a smaller number of workstations, and without increases in operations staff. The CyberGrid organizes data according to the needs of operators and/or operational activities. CyberGrid configurations can be created in a very short amount of time and used when needed, altering completely the view into the data to accommodate changing requirements or situations.

In the CyberGrid, telemetry parameters are normalized so that multivariate data can be displayed in a meaningful way on one display, and different geometric shapes are used to represent the various types of parameters (numeric, ASCII, status, binary, and so on). Visual data monitoring highlights the degree to which actual performance varies from expected behavior, making it obvious which data requires attention.

In contrast, the conventional data hierarchy shows only that alarms have been detected in various parts of the hierarchy, leaving it to the analyst to traverse each branch of the pre-configured hierarchy to determine where attention is required. In the worst case, this requires the use of multiple workstations, and even when only a single workstation is needed, the operator may not be able to group previously unrelated data from different ground stations, satellites or subsystems on one display, or to dynamically view data in new contexts.

In the CyberGrid, when a data point goes into alarm, the geometric object that represents the parameter rises on a "tower" above the grid to a height that is proportional to the degree to which it deviates from normal. The tower's color also changes to reflect the severity of the alarm. With these visual cues, a quick glance at the grid is all that's needed to alert an analyst to potential problems. By reducing the results of many graphs to a single overview, visual monitoring allows an analyst to absorb up to a thousand times more data than other monitoring techniques. Furthermore, because the interface is so intuitive, users can become adept at interacting with it very quickly — a half day of training is usually all that's needed.

An analyst can configure an alarm for a parameter when the data point is out of expected ranges (a limit alarm), when it exhibits unexpected trends, such as unacceptable rate-of-change or continuous increment or decrement (a trend alarm), or when the required number of data points have not been received within a user-defined time interval (a count alarm). In addition, an analyst can set an alarm on a "derived" parameter, applying conventional limit, trend, or count alarms to algorithmic (or logical) combinations of data. Derived parameters and the degree to which they deviate from desired/expected behavior also appear on the grid, along with the actual data.

A user can access all of the information about a data point that's in alarm by simply clicking its tower, rather than by drilling down through a hierarchy of tables and plots (see Figures 2 and 3). This allows the user to focus on the situation requiring his attention rather than on drilling for data.

ALARMS CAPABILITIES ENABLE PROACTIVE ANALYSIS

The CyberGrid environment lets analysts set alarms in flexible ways to get the information they need about the data they are monitoring.

The ability to generate alarms based on adverse trends that often occur before data goes out of limits can be extremely valuable. Analysts can set trend alarms to detect problems that evolve over time. One simple example of the use of trend alarms enables analysts to detect loss of pitch lock before it actually happens. As another example of using trend alarms, an operator that is performing a north/south maneuver on a satellite might use trend alarms to monitor the rate-of-change on the roll rate, the pitch angle, and the yaw rate. If the rate-of-change for one of these parameters increases beyond the expected rate, an alarm will indicate that the parameter may soon go out of range, giving the analyst a chance to react before a problem occurs.

Trend alarms also offer essential information when applied to eclipse operations, battery reconditioning, and battery charging after eclipse operations. For example, an alarm that monitors battery temperature and charge rate can give an analyst insight into how the batteries are performing during an eclipse operation.

Count alarms provide the means to track the number of measurements that are received for a given parameter. In the

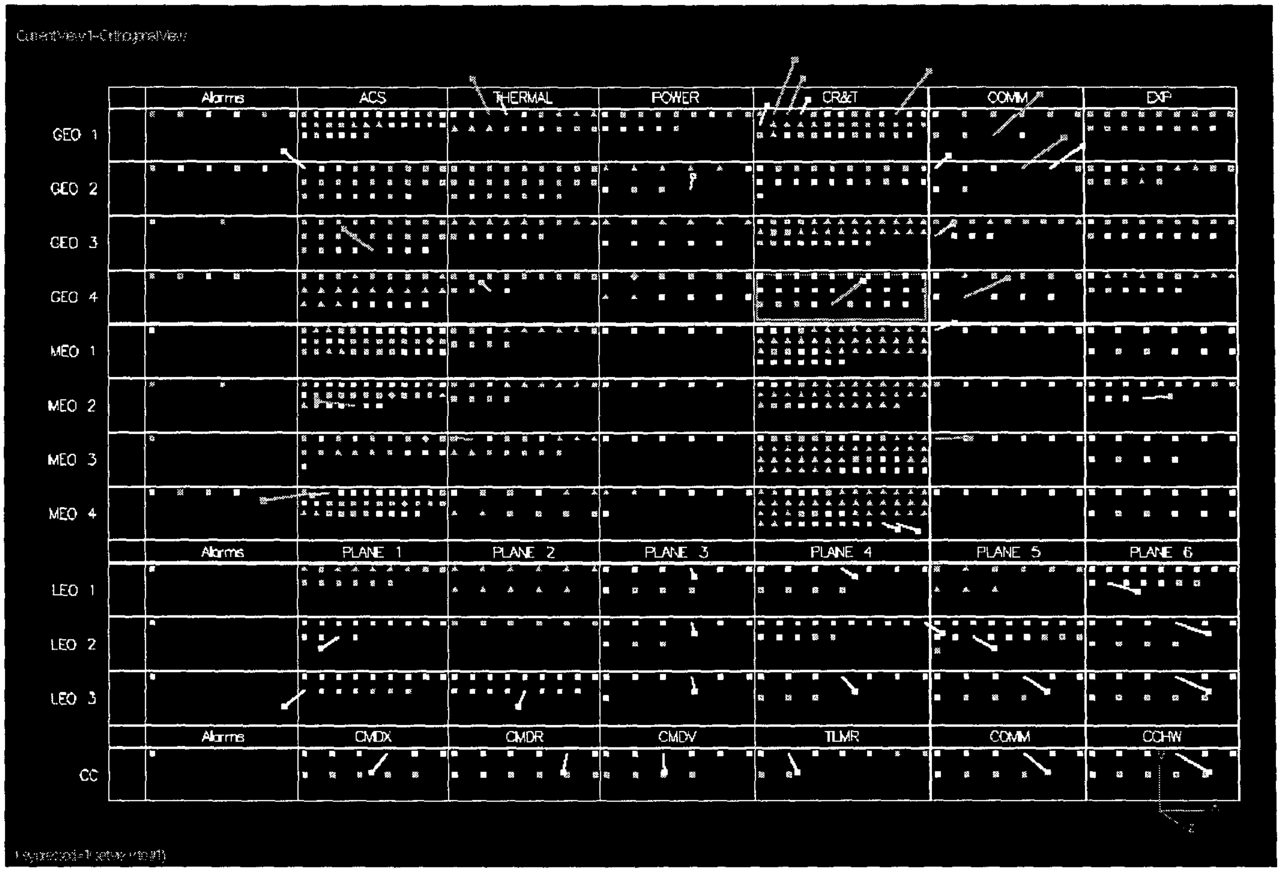

Figure 1 A CyberGrid configuration that combines data from a hypothetical constellation of LEOs, MEOs, and GEOs as well as from the control center from which they are being monitored.

case of a network operations center monitoring the amount of power customers are uplinking to a transponder, count alarms can ensure that EIRP (Effective Isotropic Radiated Power) is measured frequently enough to identify problems early, before they impact customer service or the health of the satellite.

In some situations, it's useful to set alarms on derived parameters. For example, an analyst might do this to determine which thrusters are operating most efficiently so that he can use those particular ones for a maneuver. To accomplish this task, the analyst first creates a derived parameter for each thruster to calculate the sum of the number and length of the thruster firing, along with other required parameters. He then uses off-line tools bundled with the data visualization software to calculate which thrusters are burning most efficiently. Performing this type of analysis increases revenue for the satellite operator by reducing fuel usage and adding years of life to a satellite.

The 3-D approach to telemetry monitoring allows a satellite operator to define, implement, and modify in real time all of its alarms without programming assistance or massive and time-consuming database update routines. By using limit, trend, and count alarms appropriately, a satellite operator can extend the life of a satellite by ten to twenty percent.

Benefits Of Visual Data Monitoring Beyond Satellite Operations

The technical and economic benefits of visual monitoring and analysis are readily apparent in many areas of the satellite industry.

One powerful application of visual data monitoring is network operations center monitoring. In this application, the CyberGrid displays data related to transponder and carrier usage and performance. The CyberGrid monitors and displays data for the purpose of identifying customers who are over-radiating their assigned frequency allocation with too much power. The CyberGrid enables the operations center to react immediately to such occurrences by informing the customer of the need to reduce their uplink power, so that other customers on the affected transponder will not experience down time. The quantity of data involved in this application is massive, with almost 200,000 different telemetry parameters from twenty three satellites; each satellite has hundreds of

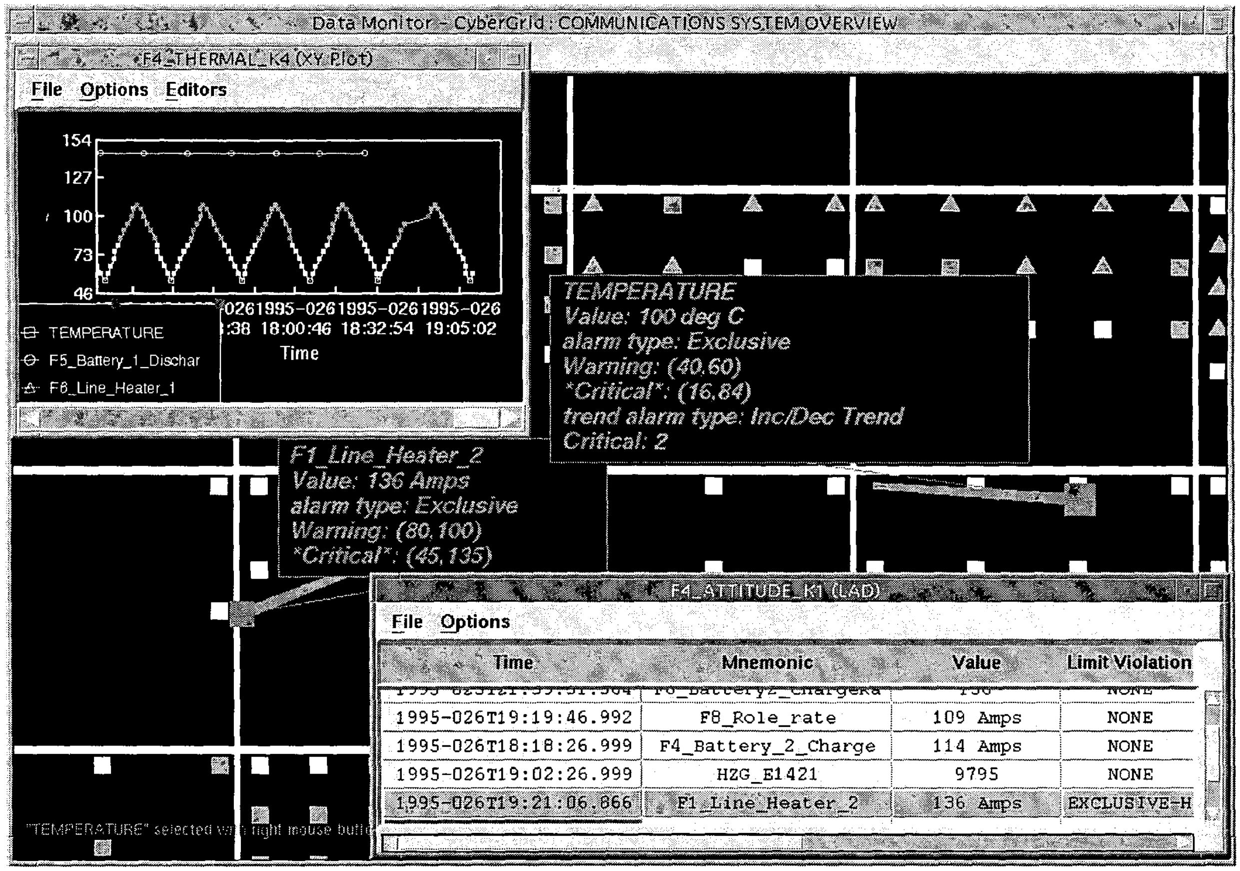

Figure 2 Additional information about any parameter in the CyberGrid can be accessed with a single mouse click. This example shows a plot and a tabular display of the type that can be created on the fly, with only a few hours of training.

transponders, and each transponder has as many as thousands of carriers. The CyberGrid provides critical information that the operator has not been able to access previously. Attempts with conventional technology failed to provide a solution because the conventional technology was never intended to be used for applications of this size.

This new technology can also be applied to ground-station monitoring. Large-scale satellite operations can use a single display to manage several ground stations across a wide geographical area. Along with monitoring RF, base-band, and antenna systems, they can also incorporate data from major satellite subsystems and inter- and intra-facility communications. The centralized display gives the operations staff an overview of the entire system and allows them to recognize and respond to problems that occur anywhere within the system.

In addition to consolidating real-time data, visual monitoring technology manages equipment status by interfacing with computers located at remote ground stations. It alerts the system operator to anomalous conditions, and allows him to forward a predefined command script to the appropriate station and hardware set. The script can switch in backup units, if required, or modify the hardware setup. Visual monitoring can also evaluate the problem and automatically forward the correct reconfiguration to the ground station. It will then verify the newly configured hardware subsystem and notify the system operator of the new configuration. If a "lights out" operation is underway, the responsible engineer will be notified of the new configuration via e-mail or pager.

This technology reduces the operator-intensive task of manually reconfiguring the ground station. It also drastically reduces staffing requirements at the central monitor and control facility, and at the remote ground stations. These benefits provide cost savings for the company and free up engineers and operators to perform other tasks.

Visual monitoring can also provide a consistent analysis tool throughout a satellite's development, testing, and deployment. Satellite manufacturers can use monitoring during the integration and test period, and the satellite operator can then employ the system in an operational environment during launch, transfer orbit, orbit test, and normal day-to-day operations. This lets the satellite manufacturer and operator use the same tools and displays when building and operating the satellite.

Traditional monitoring systems cannot provide telemetry data to an analyst at home. The visual monitoring system, in contrast, uses pager or email to provide an analyst with key information about a data point that has gone into alarm. If the

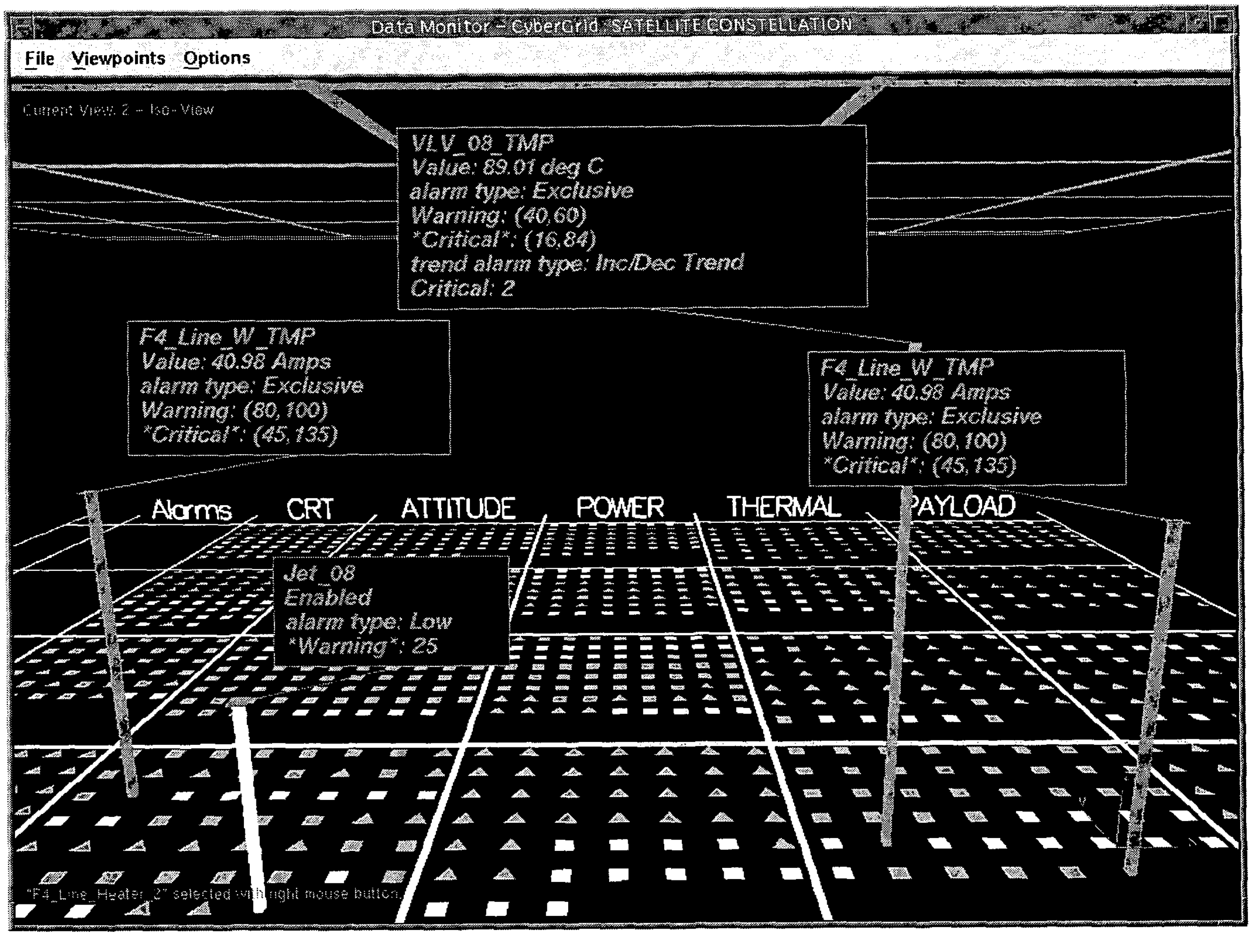

Figure 3 The CyberGrid in 3-D, from a different angle, showing quick summaries of some of the more severe alarms.

analyst needs more information or wants to examine the data in more depth, he can run the visual 3-D system at a remote location, or access a web site to which the system automatically posts information. These options allow engineers to make decisions based on actual data, regardless of whether they are on or off site.

Government and university operations are increasingly interested in running lights out operations, in which ground stations are only staffed during the day, as a way to cut costs. The visual monitoring approach greatly facilitates this type of operation. Critical telemetry parameters are monitored for alarms during the night shift. If an alarm occurs, the responsible analyst is notified via pager or email. The analyst can then retrieve data from his location and investigate the reported anomaly. This lights out systems approach can also be used by commercial satellite operations that maintain a primary and backup TT&C system. The primary control station is staffed 24 hours a day, while the backup is staffed during the day shift only. If a problem occurs at the backup station, the responsible analyst will be notified by pager or email.

CONCLUSION

As satellite constellations grow in size and complexity, operators need technology that allows them to monitor and control their spacecraft efficiently. Visual data monitoring makes data instantly available, reducing reaction time to anomalies from minutes to seconds. Anomalies are visually prioritized to draw analysts' attention to the most critical problems. With trend alarms, count alarms, alarms set on derived parameters, and the ability to consolidate data in one display, analysts can spot and correct problems anywhere in their system before they become serious. Remote monitoring is also possible through pager and email, which permits operators to run lights out operations.

Perhaps more important than the technical advances associated with visual data monitoring are the economic benefits. By effectively implementing visual data monitoring and analysis, it is easy to cut costs and/or generate additional revenue. Reduced staffing requirements allow fewer controllers to monitor larger amounts of data. With appropriate use of alarms, operators can increase the efficiency of their maneuvers and thus extend the life of their satellites. Companies who use this approach save on training and cross-training costs, and they don't need to allocate resources to develop or maintain custom software for monitoring individual resources within their system.

The most comprehensive and far-reaching design for data monitoring to date, visual data monitoring provides a solution for both the technical and economic challenges facing the satellite industry today.

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