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Upper Atmosphere Research Satellite In-Flight Dynamics Study: Lessons Learned

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The lessons learned from investigating the Upper Atmosphere Research Satellite (UARS) in-flight dynamics are summarized. Key to the success of the study was the application of knowledge discovery in database techniques. The isolation of disturbances was critical to identifying the effect of individual disturbances on the spacecraft. Numerous types of data were examined for spatial and frequency correlation as a means of discovering hidden knowledge of the dynamic behavior of the spacecraft and its instruments. Two in-flight dynamics experiments were conducted on UARS to provide the investigation with cases of isolated and combined instrument and environmental disturbances that were not attainable during the normal operation of the spacecraft. Flight data from the experiments were augmented with data collected from the first 737 days after launch. This study identified many disturbances that greatly impacted the spacecraft line-of-sight pointing but were ignored from prelaunch analysis. The spacecraft attitude response was significantly influenced by the thermal elastic bending of the solar array, the solar array gear drive, orientation of the solar array, and instrument motion. These disturbances can now be included in a knowledge base for future prelaunch analysis.

Introduction

THIS paper presents the lessons learned from investigating the Upper Atmosphere Research Satellite (UARS) in-flight dynamics. The in-flight dynamics study was commenced in 1991 by NASA to determine how well existing modeling techniques, used by industry, and experimental spacecraft modeling techniques predicted spacecraft dynamic response. The NASA-led study had General Electric Company (UARS's prime manufacturer) and Rockwell International Corporation as participants. UARS was chosen as a focus of the study because it had many dynamical attributes that were representative of many of NASA existing and future spacecraft. References 1–8 provide detailed analysis of UARS dynamics during its first three years on-orbit. On completion, the investigation examined UARS in-flight dynamic response to numerous excitations,[1–3] the impact of payload and spacecraft motion on science instrument pointing,[4,5] and the accuracy of UARS prelaunch dynamic modeling using Nastran finite element models.[6,9–12] A multipayload/multicontroller spacecraft model was also developed as a means to simulate spacecraft/systems interactions.[7] The method developed in Ref. 7 used the Dynamic Analysis and Design System (DADS®; Computer Aided Design Software, Inc.) to include nonlinear dynamics. Although the analytic tools used had very accurate plant models,[6,7] many critical disturbance inputs to the models were not included in the prelaunched analysis. One goal of this study was identification and quantification of in-flight disturbances to add to the spacecraft disturbance knowledge base. The knowledge base can be used to produce better prelaunch predictions for future spacecraft.

Knowledge discovery in databases (KDD) techniques were instrumental in discovery of many hidden characteristics of the spacecraft dynamics.[13] The initial successes from KDD were in business use. The growth in the use of KDD is due to lower cost of data storage and processing, the growing rate of data accumulation, and new data processing methods. In this study, numerous types of data were examined for spatial and frequency correlation as a means of discovering hidden knowledge of the dynamic behavior of the spacecraft and its instruments. These techniques were used to identify the spacecraft and science instrument response to numerous disturbances. Use of KDD techniques resulted in identifying the impact of UARS dynamic response on science measurement, discovering the importance of gear drive dynamics on spacecraft response, discovering latitude-specific vibration response produced by UARS solar array drive, identifying attitude response variations with orbital precession, and identifying payload–payload interaction and structure–payload interaction.[1–5] The same data that were used to produce a long-term (600-day duration) analysis of solar array thermal elastic bending effect were also used to develop the correlation between attitude response and orbital precession.[1–3]

In dynamic systems, response signatures to disturbances are implicitly cause–effect rules. Early examination of flight data demonstrated the necessity of isolating disturbances to measure their individual effects on spacecraft response and to identify cause–effect rules. Identifying the response behavior to disturbances provides designers of future spacecraft with knowledge to infer how these disturbances will influence their spacecraft. Hence, another key tool used in this study was creating isolated disturbances to quantify their influence on the spacecraft attitude response.

An in-flight dynamics experiment using UARS on 1 May 1992 was conducted to isolate all disturbances known before launch. The experiment was instrumental in identifying the solar array as a possible disturbance source. A second experiment (17 September 1993) was used as a means to provide isolated disturbance cases to examine the interaction between science instruments and to examine the effect of spacecraft dynamics on science measurements. These signatures were the both spatial and spectral. Although the spacecraft inertial reference units were primarily used, other signatures were apparent in some of the science data.[1,4,5] In addition to those isolated disturbance cases created with the aforementioned experiments, some isolated disturbances were the result of system anomalies. The solar array stopping unexpectedly on 2 June 1992 and subsequently placed in a stationary position for 42 days provided many isolated disturbances cases. The isolated disturbances made it possible to develop a knowledge base of response signatures. The results of studying the in-flight dynamics provide spacecraft designers with better insight into the impact that spacecraft instrument and environmental disturbances have on the attitude response and on the science measurements.

This paper will present the tools used to discover the aforementioned findings and how they may be used on other spacecraft. Following this introduction is a brief overview of UARS. A brief discussion of the KDD techniques will be presented next. Disturbance isolation will be discussed afterward. Examples of data mining results produced from these techniques in the frequency and spatial domain will follow. These examples include some of the key

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findings from this study. Following the examples will be conclusions that summarize the lessons learned from this study.

UARS Overview

UARS was launched in September 1991. Figure 1 shows the spacecraft in the operating configuration. A detailed description of UARS is given in Ref. 1. The spacecraft is approximately 32 ft long and 15 ft wide and weighed approximately 15,000 lb at launch. There were six subsystems/instruments that had either single-axis or biaxial gimbals. These instruments had large inertia moving about the gimbals.[1,14,15] Two of the six subsystems/instruments were continuously scanning the atmospheric limb. A single sail solar array continuously rotated about an axis parallel to the spacecraft pitch axis. The other three gimballed instruments/subsystems were tracking targets (sun, stars, and relay satellites). Motion of the six spacecraft gimballed instruments and subsystems produced measurable attitude responses that were rigid body and/or from the excitation of UARS two large flexible appendages.[1–3]

The complexity of UARS dynamics can be understood by examining the events of one orbit. Figure 2 shows all events that imparted disturbances to the satellite during the first orbit of 28 January 1992. The disturbances that were known before launch to have expected influence on the spacecraft dynamics are annotated in Fig. 2. UARS is in a 57-deg inclination orbit at 364 miles. During this orbit, all UARS instruments and subsystems were operating nominally. The Microwave Limb Sounder (MLS) and the High-Resolution Doppler Imager (HRDI) atmospheric limb scanning imparted continuous repetitious disturbances to the spacecraft throughout the orbit. These events are described in Table 6 of Ref. 1. Because of the continuous

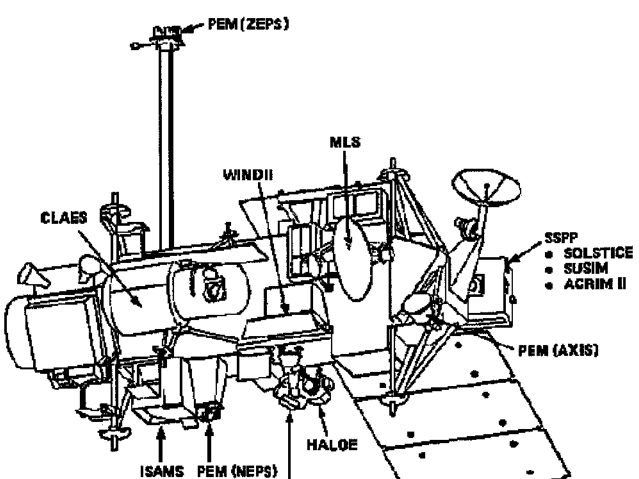


Fig. 1 UARS.

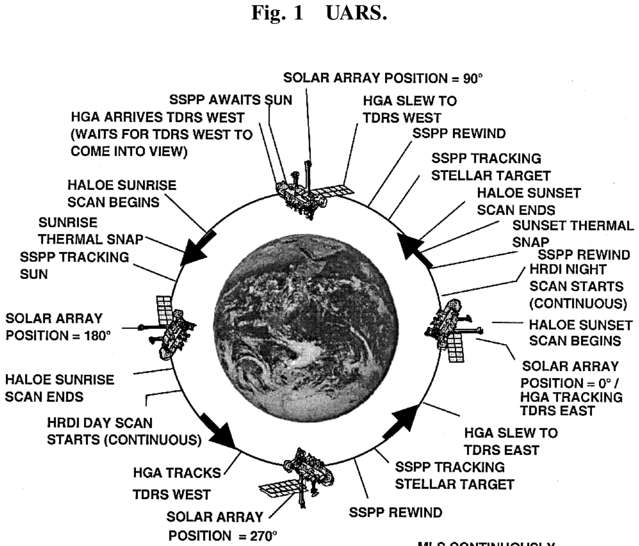


Fig. 2 Orbital events during the first orbit of 28 January 1992.

repetitive disturbance caused by HRDI and the MLS disturbances, there were no isolated disturbances to develop a knowledge base of response signatures. To understand the influence that each had on the spacecraft, it was necessary to isolate them. Isolation of disturbance events was one of the objectives of the two aforementioned in-flight dynamics experiments.

UARS's attitude determination and control subsystem had numerous sensors onboard for attitude determination.[1–3,14,15] These included an Earth sensor assembly module, fixed-head star trackers, and an inertial reference unit. However, because of limitations in either sampling rate or resolution, the only means of measuring attitude suitable for studying jitter was with the inertial reference unit gyros at the aft end of the spacecraft. These gyros had a resolution of 0.05 arc-s with a sampling rate of 7.8125 Hz. The spacecraft had a pointing requirement of maintaining its roll attitude within 4 arc-s of displacement for a 2-s period.

KDD Overview

KDD is the nontrivial extraction of implicit, previously unknown, and potentially useful information from data.[13] It is the process of discovering hidden knowledge, unexpected patterns, data clusters, and new cause–effect rules from large databases. Knowledge discovery in databases has six stages: data selection, data cleaning, data enrichment, coding, data mining, and reporting.[13] Data selection is the stage of selecting the right data for KDD. In this study, data selection consisted of selecting the telemetry records from the UARS Central Data Handling Facility (CDHF) at the Goddard Space Flight Center, for example, roll, pitch, and yaw gyro counts.[14,15] Data cleaning is the process of removing noise, errors, and incorrect input from a database. For example, some UARS instrument data had vibrational perturbations superimposed on the rigid-body rotational motion. The rigid-body motion was removed from rotational data to analyze its vibrational behavior. Data enrichment is the process in which new data are added to the existing selected data. The data enrichment process was not used in this study. Coding transforms or simplifies data to prepare it for analysis and/or machine learning. Coding in this study consisted of converting CDHF binary files to MATLAB® files that have meaningful values. All analysis performed by NASA was with the MATLAB numeric computation and visualization software by MathWorks, Inc.

Data mining is the next stage, and it is the actual discovery phase. The goals of data mining include identifying and/or discovering structure, characteristics, tendencies, anomalies, and relationships among data. Myriad techniques can be used for data mining. These can include statistical; machine learning; visualization, for example, scatter plots; pattern recognition; and clustering tools. Data mining can be used to identify behavior rules of databases, that is, cause–effect rules. Reporting is the application of using results from data mining to modify or redirect the mining algorithm to examine new data or examine data in a new manner. Discovery of characteristics to spacecraft dynamics can be used to hypothesize the existence of other features. Hence, the database can be further mined for proof of new hypotheses. Because the database is a record of physical phenomena, data mining can also be the genesis to experimentation.

Another key element of KDD is the data warehousing. Data warehousing is the repository of historic subject-oriented data. Although UARS CDHF is an operational warehouse, it is not a data warehouse.[13–15] The CDHF is the facility for ingesting, cataloging, and storing science, engineering, and spacecraft data.[14] The CDHF was developed to be an operational facility that has a database that is constantly being updated with new data. A data warehouse is designed for decision support. Data in a data warehouse are nonvolatile, integrated, subject oriented and time dependent.

An historical example of data mining used in dynamics, or more precisely astronomy, is that of a study performed by Johannes Kepler. In 1609, Kepler published *Commentaries on the Motions of Mars.* The study was a result of mining and analyzing data collected over 20 years by the astronomer Tycho Brahe. Brahe's data included continuous and detailed records of the sun, moon, and planetary positions. Data on Mars were most extensive. Using the Mars data, Kepler discovered the physical characteristics of planetary orbits that are now known as Kepler laws of planetary motion (see Ref. 16). The next section presents results on using data mining techniques on data collected during isolated disturbances. Mining results were instrumental in identifying physical characteristics of the spacecraft.

Disturbance Isolation

Three events resulted in opportunities to measure and discover all disturbances that significantly perturbed the spacecraft's attitude. The first event was an in-flight experiment. The objectives of the experiment were to isolate all disturbances known before launch, to generate combinations of disturbances, to create spacecraft dynamic responses suitable for system identification, to examine spacecraft quiescence, and to identify any disturbances not known before launch. The experiment, performed 1 May 1992, was accomplished by scheduling the operation of the MLS and the HRDI such that they would be stationary at prescribed times. Data gained from the first disturbance experiment showed that the vibration level was still persistent when all disturbances known before launch were temporarily shut down, including the MLS scanning. Spacecraft vibration was referenced in terms of jitter. Spacecraft jitter is the angular excursion of an instrument's line of sight in a reference time interval (such as a sampling time period). During the 34-min period when all major disturbances known before launch were quiescent, roll jitter exceeded 15 arc-s/(2-s), and yaw jitter exceeded 6 arc-s/(2-s) (Refs. 1 and 2). Furthermore, power spectral density frequency analysis indicated strong excitation of the solar array fundamental flatwise and edgewise modes.[1,2] The variations of the vibration pattern observed in one orbit were repeated in the next.[2] These repeated pattern variations were observed when all known disturbance were quiescent and the pattern extended the duration of an orbit. The dominant trends in the jitter patterns were independent of any subsystem or instrument dynamics but varied with solar array position. Hence, it was concluded via process of elimination that the solar array (which rotates once per orbit) was the source of the excitation.

A second event used to isolate disturbances was unplanned. On 2 June 1992, the solar array stopped rotating unexpectedly. Before stopping, the roll gyro measured attitude displacements that exceeded 1 arc-s during the 0.128-s sampling intervals. The significant reduction in jitter, when the solar array stopped rotating, validated the conclusion that the solar array was the disturbance source producing the constant excessive jitter levels.[1,2] The prime contractor for the UARS, General Electric Company, investigated the cause of the anomaly and found that the solar array drive stepper motor output (which had 23 pulses/s) transmitted through the harmonic drive (which had a 100:1 reduction ratio) produced a harmonic drive output of 0.23 pulses/s. The harmonic drive output frequency resonated the solar array edgewise and flatwise modes whose resonant frequencies were approximately 0.25 Hz each. Stopping the solar array eliminated the excitation source. The reduction in vibration also reduced the solar array flexing from being transmitted back to the gear drive.

The discovery of the solar array gear drive influence on the spacecraft response greatly impacted the study. The disturbance due to the solar array gear drive produced the second highest level of attitude perturbation. Thermal bending of the solar array during terminator crossing produced the highest attitude perturbation.[1–3,8–11] Unlike the thermal snap, which lasted less than 3 min, the disturbance due to the solar array gear drive was continuous. After the solar array anomaly, the array was kept stationary for 42 days. During that interval, some of the instrument disturbances were isolated. However, to collect data for the isolation cases that were the objective of the first experiment, another in-flight dynamics experiment was performed on 17 September 1993.

The planned isolated instrument disturbances occurred during an approximately monthly standard procedure of turning the spacecraft 180 deg about the yaw axis. Part of the second experiment was conducted during the spacecraft yaw maneuver to examine spacecraft dynamics when the solar array was stationary. The second experiment attempted to quantify the spacecraft motion impact on the science instrument measurements and provided more cases to study instrument interaction. The three isolation events (two experiments and the solar array anomaly) resulted in identifying and isolating all major disturbances on the spacecraft. The isolated disturbances provided the flight data necessary to begin analyzing the influence that the disturbances had on the spacecraft response. The data were used as part of the database for the data mining techniques that will be discussed in the next section.

Use of knowledge gained from examining the spacecraft response produced by the solar drive was also used to identify the disturbance from the high-gain antenna drive. The jitter resulting from the high-gain antenna exceeded 0.8 arc-s/(2-s). The amplitude was a small value with respect to the UARS pointing requirement of 4 arc-s/(2-s). The identification of the disturbance is important for future spacecraft because the response amplitude will be higher if the disturbance has a higher transmission to the solar array modes or if the spacecraft is smaller. Before launch, UARS disturbances considered the disturbance generated by solar array and high-gain antenna gear drive mechanisms to be negligible. The assumption was based on the very low rotation rates of the drives. The solar array, the high-gain antenna, and the solar-stellar pointing platform rotation rates were approximately those of the orbital rate, (that is, one complete revolution per orbit at 0.06 deg/s). Hence, the output frequencies of their gimbals were significantly less than the fundamental frequency of the spacecraft structural modes, which were measured between 0.21 and 0.29 Hz (Refs. 1, 3, and 6).

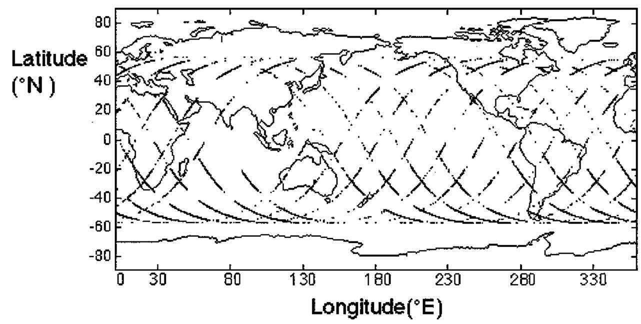
Prelaunch analysis had predicted that the MLS would produce the largest spacecraft jitter response [2.6 arc-s/(2-s) about the roll axis]. The peak roll jitter observed for day 737 was 2.6 arc-s/(2-s). During the day when these data were measured, the solar array was stationary. All other disturbances were temporarily stopped. The response produced during this event agreed with the prelaunch analysis.[1,9,10] Hence, with the solar array drive inactive, the spacecraft roll attitude jitter would constantly maintain the required line-of-site pointing.

Data Mining Results

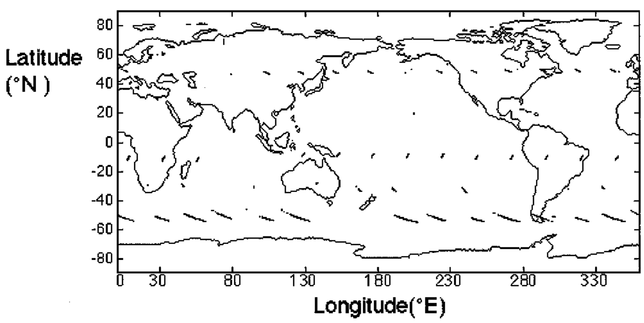
Data mining provides a means of identifying spacecraft in-flight characteristics and behavior from examining relationship between data types and/or identifying data patterns. Because all data are time registered, data mining allows all data to be correlated. This characteristic provides an opportunity to identify physical phenomena hidden in the data. This section presents results from data mining using data collected from the UARS spacecraft. One of the first results from mining is that the jitter levels were latitude specific.

Spacecraft gyro data are measured and cataloged as time registered. The spacecraft latitude is also time dependent. Figure 3 is an example of examining two time-registered independent data to ascertain if any relationship exist. Figure 3 shows mapping of points on the UARS ground track, 22 January 1992, that exceeded certain jitter level thresholds. Thresholds for Figs. 3a and 3b are 4 arc-s/(2-s) (minimum spacecraft jitter requirement) and 10 arc-s/(2-s), respectively. From Fig. 3, it can be seen that the jitter values exceeded the thresholds only at certain latitudes. The 10 arc-s/(2-s) roll jitter threshold (Fig. 3b) was exceeded at latitudes of 57° S (sunrise thermal snap), 46° N (sunset thermal snap), 10° S, and 38° S. Figure 3 shows that there is a relationship between the jitter level and latitude. The correlation of jitter to groundtrack latitude was valid for the short term (approximately 1 day) due to the orbital precession. Many science measurements are referenced to latitude. Because the jitter response (Fig. 3) was also specific to latitude, it seemed logical to determine if the spacecraft dynamic response had any influence on science data collection. The results from Fig. 3 were the genesis of a study to examine the impact of spacecraft dynamic response on science measurements.[5]

The study in Ref. 5 is an example of knowledge gained from mining the database being used to further examine the relationship between physical phenomena. The data collected from the 1 May 1992 experiment was mined to determine if spacecraft dynamics could be inferred from the Halogen Occultation Experiment (HALOE) fine sun sensor. Obtaining data cases to examine the influence of dynamic response of science measurements was not an objective of the experiment but was a serendipitous result. During the experiment, the MLS antenna was kept stationary through two successive orbital sunsets. During the first sunset, the HRDI instrument was also



a) **Roll jitter exceeding 4 arc-s over a 2-s interval**



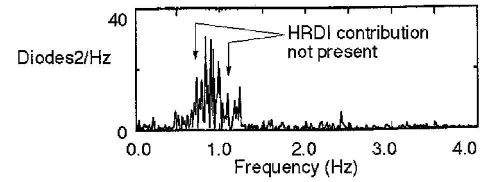
b) **Roll jitter exceeding 10 arc-s over a 2-s interval**

Fig. 3 Ground track of roll jitter on 22 January 1992.

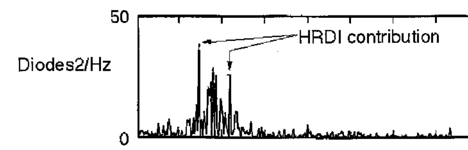
kept stationary. During the next sunset, HRDI performed its normal periodic atmospheric limb-viewing scans. HALOE performed measurements during both sunsets. Examination of HALOE fine sun sensor data for the two orbits demonstrated that the HRDI scans perturbed the HALOE fine sun sensor measurements.[4,5]

During the second sunset of the experiment, HRDI was operating with a scanning frequency of 0.083 Hz, which was outside the 0.01-Hz bandwidth of the UARS attitude control system.[1,4,5] Therefore, HRDI produced an unattenuated disturbance that was transmitted to the spacecraft structure. The HALOE gimbal motion was actively controlled. The sun's relative position measured by a fine sun sensor provided feedback. The solar disk position was measured every 0.016 s. The HALOE gimbal controller corrected the targeting of the sun every 0.128 s. Hence, every 7 of 8 records of the solar position on the fine sun sensor captured the sun's apparent harmonic motion (due to pointing corrections) modulated by the cyclic perturbations caused by HRDI scanning and the solar array vibration. Figure 4 shows power spectral densities of the frequencies associated with the fine sun sensor measurements during the two successive sunsets. Figure 4a results were from the fine sun sensor sunset measurements with HRDI stationary, and Fig. 4b results were from the sun sensor sunset measurements with HRDI scanning at a frequency of 0.083 Hz. The sidebands of Fig. 4b represents the HRDI modulations to the HALOE tracking frequencies (0.8 and 1.0 Hz). Unlike the traditional method of data mining, the results just presented are derived from data mining the frequency content of the database. The mining results from examining the HALOE fine sun sensor data were the genesis of an experiment, conducted 17 September 1993, to ascertain if spacecraft response could be identified in science data.

For the experiment, the MLS antenna was controlled so that it maintained a fixed line-of-sight pointing to allow examination of the influence of the spacecraft motion on its radiance measurements. The fixed MLS line-of-sight pointing emulated the Wind Imaging Interferometer (WINDII) line-of-sight pointing. MLS had a roll jitter requirement of 18 arc-s/(2-s), a sampling rate of 0.5 Hz, and a spatial resolution of 3–6 arc-s. Thus, MLS had a sufficient spatial resolution and sampling interval to discern spacecraft dynamic response. Results of the experiment are shown in Fig. 5. Figure 5 shows the time history of roll jitter and the radiance measurements taken by MLS. Perturbation of the roll attitude resulted in perturbations of the radiance measurements. The disturbances that caused the perturbations are annotated between the graphs. The sunset solar



a) **HRDI is stationary**



b) **HRDI in night scan mode**

Fig. 4 Power spectral density for HALOE fine sun sensor telemetry, 1 May 1992 (one diode = 16.2 arc-s).

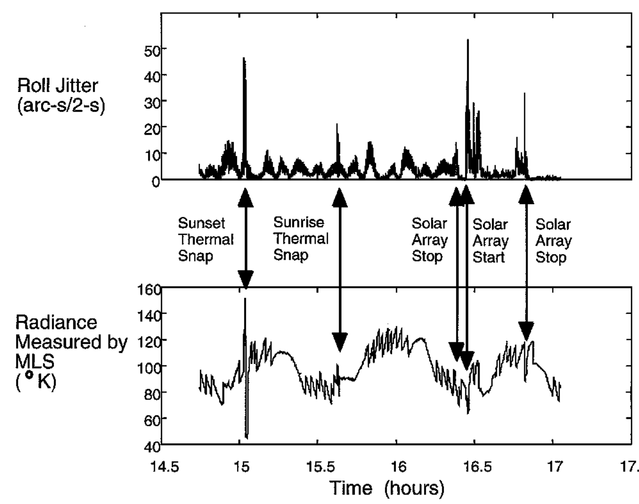
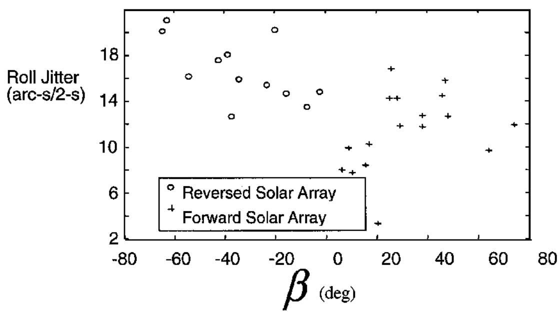


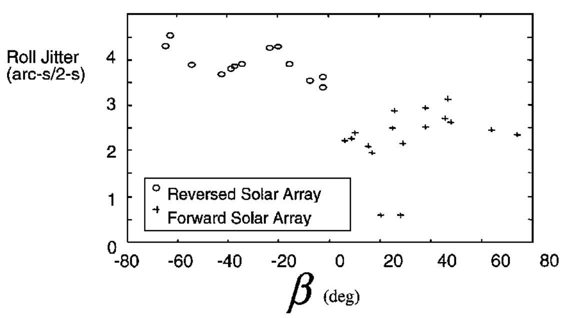
Fig. 5 Spacecraft roll jitter on 17 September 1993 and MLS radiance measurement.

array thermal snap produced a pronounced perturbation in the radiance measurement. The sunrise solar array thermal snap produced a noticeable increase in the measured radiance, but the perturbation was not as pronounced as that caused by the sunset snap. When the solar array stopped and restarted, a reduction of the measured radiance occurred. The next stopping of the solar array also resulted in a noticeable reduction of the measured radiance. Except for the sunset snap, the other perturbations could be misinterpreted as actual atmospheric anomalies. However, by correlating the jitter time history with the radiance time history, the spacecraft response signature can be easily identified. The low-frequency radiance variation in Fig. 5 is an orbital effect due to the spacecraft gravity-gradient torque not being completely removed by the attitude control system.[5] The aforementioned results demonstrate that data mining could be used to prove a hypothesis and be further extended to become the genesis of experimentation. Data mining can also provide insights to a system's performance by examining how changes to the system produce different responses.

Mining the UARS database was the means by which it was revealed that the jitter response was dependent on the direction of the solar array rotation. Figure 6 shows the maximum and average roll jitter levels for days 128–737 past the launch of UARS. The effect of the solar array rotation direction is apparent. When the solar array was rotating in reversed direction, the jitter was higher than when the solar array was rotating in the forward direction. The average and maximum roll jitter shown in Fig. 6 excluded jitter during the thermal bending of the solar array. Because of the precession of the orbit plane, the β angle swept out an angle of ± 80.45 deg. The angle β is the complement of the angle between the orbit normal and the Earth-to-sun vector. At large values of the β angle, solar array energy collection and sun impingement on the payloads became a



a) Maximum roll jitter



b) Average roll jitter

Fig. 6 Spacecraft roll jitter variation with β angle for days 128–737 past launch.

problem. To alleviate the problem, the spacecraft was rotated 180 deg about its yaw axis approximately every 30–36 days. After each yaw maneuver, the direction of solar array rotation was changed. The significance of this finding is that the UARS pointing requirement was violated more during days when the solar array was rotating in the reverse direction. Hence, the accuracy of science measurements that had to adhere to the 4 arc-s/(2-s) requirement varied approximately every other month.

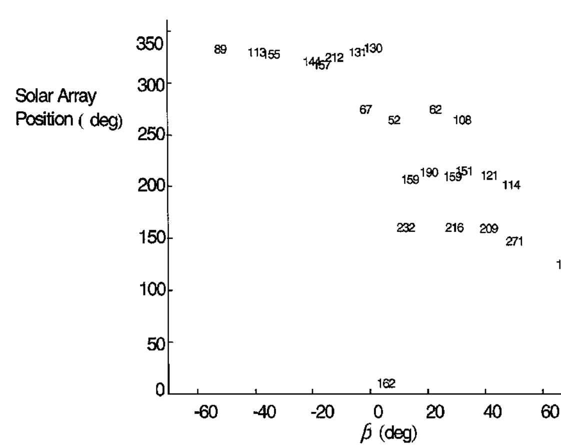
The resulting attitude perturbation was also dependent on the β angle and the solar array position.[1,3] Because the orbit plane precessed between yaw maneuvers, the tracking instruments varied their tracking trajectories correspondingly. The change in tracking trajectories produced a corresponding change in the spacecraft response. Jitter measurements during thermal bending of the solar array were also excluded from the results shown in Fig. 6. The dominant trend observed was that as the magnitude of the β angle increased, the roll jitter increased. It can be inferred from Fig. 6 that between yaw maneuvers, the jitter levels grew monotonically.

Reference 6 measured the free-decay damping of the spacecraft response to the solar array stopping as 2.8% and attributed this damping to the solar array edgewise mode of vibration. However, the friction in the gear drive or clutch was the probable cause of the high damping ratio. Because the edgewise mode of vibration was constrained by the gear drive, all damping effects would have significantly attenuated structural vibration of the solar array edgewise mode. Furthermore, when the gear drive clutch was locked and other disturbances were active, there was no high value of damping observed for the solar array flatwise and edgewise modes. The damping effect of the gear drive countered the resonating effect of the solar array harmonic drive output. Friction in the gear drive attenuated energy placed into the solar array at the resonant frequency by the harmonic drive. The result was that the solar array had large but bounded levels of vibration. Therefore, any catastrophic damage to the solar array drive was prevented. However, the excessive flexing of the solar array transmitted through the gear drive could reduce the life of the drive. The results from Fig. 6 also can lead one to infer system status, for example, the solar drive shaft clutch may have more slippage when the array is rotated backward.

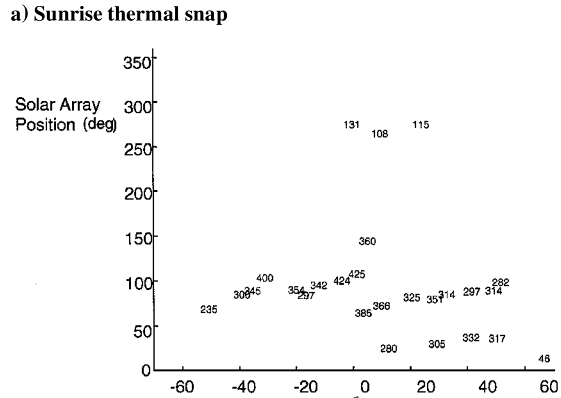
Knowledge gained from investigating the malfunction of the solar array drive and the excessive roll vibration response has been used to redesign the solar array drive on the Earth Observing System AM spacecraft (EOS-AM), which had a design similar to UARS. The design of EOS-AM before the solar array malfunction (2 June 1992) used a solar array gear drive with a harmonic drive output frequency of approximately 0.25 Hz. The EOS-AM solar array fundamental mode is approximately 0.18 Hz. Hence, that EOS-AM solar array drive could have resonated the solar array in a manner similar to UARS. The analysis of UARS flight data and gear drive design strongly indicated that the harmonic drive output of the UARS solar array drive was responsible for the solar array vibration. The EOS-AM solar array drive was redesigned to eliminate the potential resonance problem before launch.

A final result presented in this paper that was gained from data mining is that of further understanding thermal elastic bending of appendages by examining the spacecraft response due to the bending. Thermal elastic bending of the UARS solar array had the most pronounced impact on the spacecraft attitude. This disturbance had been observed on other spacecraft with a single large solar array mounted to a central rigid hub such as Landsat-4 and Landsat-5 (Ref. 8). Thermal elastic bending resulted from the temperature gradient created when UARS entered or exited the Earth's terminator. The thermal elastic bending is also called thermal snap because of its short duration relative to the orbit duration. References 1, 3, 8, and 11 give a detailed discussion of the solar array thermal elastic bending impact on spacecraft attitude. Data from orbits were examined at approximately 15-day intervals from day 128–737 past launch. The trough-to-peak roll attitude displacement and displacement duration were measured for each orbital sunset and sunrise thermal bending event. The displacements were then correlated with the β angle and solar array orientation during the displacement. Figures 7a and 7b show the trough-to-peak roll attitude displacement resulting from thermal bending of the solar array during orbital sunrise and sunset, respectively. The displacements are annotated (rounded to nearest arcsecond) for the respective β angle and solar array position. The magnitude of roll attitude perturbation was dependent on the β angle and solar array orientation with respect to the drive shaft.

During orbital sunrise (Fig. 7a) the displacement was larger for β angles near 17 deg and solar array orientations of 160 deg. The



a) Sunrise thermal snap



b) Sunset thermal snap

Fig. 7 Variation of trough-to-peak roll attitude displacement with solar array position and β. (Numbers indicate displacement in arcseconds.)

sunrise attitude displacements were as high as 271 arc-s. During orbital sunset (Fig. 7b) the displacement was larger for β angles near 0 deg and solar array orientations near 90 deg. The sunset attitude displacement was as high as 425 arc-s and duration of 47 s. The perturbation events were usually 180 s in duration. Duration was dependent on the β angle and the solar array orientation with respect to its drive shaft. The solar array completed approximately one-third revolution between sunset and sunrise. When the solar array was oriented at 90 deg (or a 270-deg position) for maximum electrical power production, it also experienced the maximum attitude perturbation for sunset (sunrise).

Conclusion

This paper has summarized a six-year study of the UARS in-flight dynamics. Data from the first 737 days past launch was used in the investigation. The investigation included two in-flight experiments on 1 May 1992 and 17 September 1993, which measured responses caused by prescribed disturbances on the satellite, the interaction between instruments, and the effect of spacecraft dynamic response on science measurements. The spacecraft attitude response was significantly influenced by the thermal elastic bending of the solar array, the solar array gear drive, orientation of the solar array, and instrument motion.

KDD techniques were instrumental in the discovery of many hidden characteristics of the spacecraft dynamics. This study has demonstrated that when an infrastructure is already in existence for the operational collection of the telemetry from a spacecraft, data mining activities can commence with marginal effort. Massive amounts of engineering and scientific data were collected from the spacecraft as part of its standard operations. Unless anomalies exist in the performance of the spacecraft, very little of the collected data are examined to understand spacecraft dynamics. Spacecraft telemetry should be made more readily available to a broader audience. Many of the results presented greatly impacted the spacecraft attitude but were not included in prelaunch analysis. A significant lesson learned from the entire study is that a great deal of relevant information would have remained buried if not for the data mining that occurred in this study. Studies such as this should be encouraged for all NASA missions. The enhancement to the spacecraft dynamics knowledge base would be significant.

In-flight experiments on UARS demonstrated the direct effects of spacecraft response on science measurements. The experiment was developed as a means to prove a hypothesis that was derived from examining the data. Perturbations of roll attitude resulted in perturbations in MLS radiance measurements. The spacecraft motion influence on radiance measurements was readily identifiable when the roll attitude response was directly correlated with the radiance measurements. However, many of the science measurements are correlated to other measurements and are directly referenced to latitude and longitude. Any spacecraft response influence on the science data could easily be ignored. The impact of spacecraft dynamic response and instrument motion on the measurement of another instrument was demonstrated by examining the frequency content of the HALOE fine sun sensor.

Thermal elastic bending of the UARS solar array produced the most pronounced impact on the spacecraft attitude and occurred during the orbital sunrise and sunset. The sunset and sunrise attitude displacements were as high as 425 and 271 arc-s, respectively, about the spacecraft roll axis. The perturbation events were usually 180 s in duration. The UARS solar array gear drive was the second largest disturbance contributing to spacecraft attitude perturbations. Prelaunch analysis considered that disturbance to be negligible and concluded that the MLS antenna scan was the dominant continuous excitation source. Unlike the thermal elastic bending, the disturbance that the gear drive produced was continuous. The free-decay damping of the solar array (after the solar array drive disturbance stopped temporarily) was 2.8%. The concurrent damping and excitation of the varying edgewise and flatwise vibration modes resulted in excessive but bounded jitter levels. The damping prevented any catastrophic damage to the solar array caused the gear drive resonating the array. However, the flexing of the solar array panel transmitted through the gear drive may have reduced gear drive life.

The solar array gear drive produced a latitude specific vibration pattern. Because the science measurements are referenced to latitude, the latitude specific jitter could result in anomalies in the science data being incorrectly attributed to atmospheric phenomena. Backward rotation of the solar array resulted in higher jitter levels than forward solar array rotation. From the difference in jitter levels resulting from the different rotation directions, one can infer the status of the solar array drive. For example, more drive shaft clutch slippage occurred during solar array backward rotation. One trend observed from the flight data was that as the β angle increased, the jitter level grew monotonically. This growth was possibly due to the tracking instruments adjusting the tracking trajectories to accommodate the precession of the orbit. The high-gain antenna gear drive dynamics was also identified as an excitation source.

The lesson learned from analyzing the response produced from system gear drives is that spacecraft designers should identify and catalog frequencies from all instruments and system gear drive outputs at each stage of gear reduction to determine whether any structural resonances occur near intrument frequencies. Knowledge gained from investigating the malfunction of the solar array drive and the excessive spacecraft roll vibration response had been used to redesign the solar array drive on the EOS-AM satellite. UARS and Landsat (4 and 5) are two cases in which observed anomalies in spacecraft performance or response have been used to improve subsequent spacecraft design. However, the two cases demonstrate the need for studying in-flight dynamics to produce a knowledge base for improving spacecraft design. Furthermore, as instrument-pointing requirements become more demanding, spacecraft disturbances that were previously less important are becoming limiting factors in the quality of science data. Lessons learned from this study can greatly improve the future of spacecraft design by including previously ignored dynamics that in-flight measurements have shown to dominate the response. Furthermore, the methods used in this study can be applied to the data collected from other spacecraft.

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