Paper ID No. SO96.7.03

ENHANCING THE ACE CONTROL CENTER FOR THE MULTIPLE USES OF SPACECRAFT INTEGRATION AND TEST AND MISSION AND SCIENCE OPERATIONS.

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ABSTRACT. NASA, at the direction of its Administrator, is undertaking a grand challenge of change for "faster, better, cheaper; strong emphasis is now being placed on staying within cost projections while still meeting schedule and performance goals. This led NASA to mandate fixed-price, capped-cost programs. The Advanced Composition Explorer (ACE) is the first mission to be funded in this manner. Consequently, the ACE Project has sought novel approaches and techniques to constrain costs without compromising schedule or science goals. A key approach that has been adopted is novel, multiple reusage of the ACE control center subsystem.

ACE will use a version of the Transportable Payload Operations Control Center (TPOCC) for its mission operations. It was determined in Phase B of the ACE Project that a potential existed for substantial savings if the adaptation of the TPOCC for ACE Mission Operations could include adapting it as well for use as the primary component in the Ground Support Equipment for Integration and Testing of the ACE Spacecraft and, at the same time, also adapting it be the basic component in the ACE Science Center; thus, realizing three separate uses for essentially the same system. Implementing this approach required enhancing the TPOCC requirements, significant changes in its development schedule, and changes in the allocation and activities of personnel responsible for development of ACE operations. This paper discusses how these issues were addressed, the unforeseen problems that have been encountered, how these problems have been resolved, and an evaluation of what this approach portends for application to future missions.

1. ACE OVERVIEW

The Advanced Composition Explorer (ACE) is one of several Explorer missions funded by the Office of Space Science of the National Aeronautics and Space Administration (NASA). The primary purpose of the ACE observatory is to determine and compare the isotopic and elemental composition of several distinct samples of matter including the solar corona, the interplanetary medium, the local interstellar medium, and galactic matter. Observations will span a broad energy range from solar wind to galactic cosmic ray energies (~100 eV/nuc to ~500 MeV/nuc) for Hydrogen to Zinc (Z=1 to 30) during both solar active and solar quiet periods. ACE will provide the first extensive tabulation of solar isotopic abundance based on direct sampling of solar material. Nine instruments comprise the primary ACE payload. See Table 1.

There are two secondary payloads: the Spacecraft Load and Acoustic Measurement (SLAM) which will report the first five minutes of forces acting on the spacecraft during launch and a second, the Real Time Solar Wind (RTSW), which will continuously downlink a subset of the ACE payload data in real-time to NOAA to provide NOAA the current characteristics of the solar wind. The operational orbit of ACE will be a halo orbit about the L1 libration point between the sun and the earth-moon barycenter. Launch will be in August, 1997, from the Eastern Test Range on a Delta II 7920. The transfer trajectory to reach L1 will take about 100 days.

Name	Instrument	Lead Co-I.	Affiliation
CRIS	Cosmic Ray Isotope Spectrometer	A.C. Cummings	California Institute of Technology
SIS	Solar Isotope Spectrometer	A.C. Cummings	California Institute of Technology
ULEIS	Ultra Low Energy Isotope Spectrometer	G.M. Mason	University of Maryland
SEPICA	Solar Energetic Particle Ionic Charge Analyzer	E. Moebius	University of New Hampshire
SWIMS	Solar Wind Ion Mass Spectrometer	G. Gloeckler	University of Maryland
SWICS	Solar Wind Ion Composition Spectrometer	G. Gloeckler	University of Maryland
EPAM	Electron, Proton, and Alpha Monitor	R.E. Gold	Johns Hopkins University
SWEPAM	Solar Wind Electron, Proton, and Alpha Monitor	W.C. Feldman	Los Alamos National Laboratory
MAG	Magnetomete	N.F. Ness	University of Delaware

Table 1. ACE Instruments and Lead Co-Investigators

Design of ACE is based on the requirement for a minimum two year mission life with a goal of five years. Primary mode of communication with ACE will be through the Deep Space Network using the 26 and 34 meter networks. Nominal operations will have one pass per day with a duration of approximately 3.5 hours. Command uplink is at the rate of 1000 bits per second. There are three downlink rates: a low rate of 434 bits per second; real-time data transmission at 6,944 bits per second; and a recorder playback rate of 76,384 bits per second. Capture and processing of the RTSW data, which is downlinked continuously at 434 bits per second except during the daily 3.5 hour pass, is the responsibility of NOAA. Telemetry uplink and downlink conforms to CCSDS packet standards.

2. GROUND OVERVIEW

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) is building the spacecraft under a Goddard Space Flight Center (GSFC) contract and is responsible for integration and testing (I&T) of the spacecraft and its instruments and providing the I&T Ground Support Equipment (GSE) system whose chief component is the ***ITOCC*** —the Integration and Test Operations Control Center. Development of the instruments is being managed by the Space Research Laboratory at the California Institute of Technology (CIT).

Spacecraft Operations will be performed at the GSFC in the ***ACE MOC*** —the ACE Mission Operations Center. Level-0 processing of payload data is performed in the ACE MOC. The data is then transmitted to the ***ASC*** —the ACE Science Center— at the California Institute of Technology. The ASC is responsible for scientific processing of the data, making the data products available to the ACE Science Analysis Remote Sites (ASARS), and transmitting instrument commands to the ACE MOC for transmission to the on-board ACE Command & Data Handling (C&DH) Data Processing Unit (DPU) where they are then transmitted to the desired instruments' DPU.

The basic component for the ACE MOC will be the Transportable Payload Operations Control Center (TPOCC), a Unix based system, which has been a foundation system for most spacecraft control centers at the GSFC for the past several years. As the NASA space program matured, GSFC has found itself increasingly tied to obsolete computers hosting unique systems supporting aging spacecraft. A primary goal of the TPOCC which is computer independent is to enable a control center to upgrade its computer equipment and rehost the software without having to completely rebuild the software. TPOCC provides the standard control center functions. Mission unique software components are developed and then interfaced with TPOCC. A secondary goal of TPOCC usage is to enable replacement of TPOCC itself with upgraded versions

3. GROUND SYSTEM ANALYSIS

Given the NASA mandate to reduce budgets and conform to standards, the ACE Ground Project decided to build a Common system, based upon TPOCC, to support the three ground elements, the JHU/APL ITOCC, the CIT ASC, and the ACE MOC which is being built by the Mission Operations & Data Analysis (MO&DA) Directorate at GSFC. This concept should reduce development costs enabling GSFC and JHU/APL to live within NASA budget constraints and the ACE Science Team to relegate more resources to scientific investigations and less resources to developing software data analysis tools. To encourage the ASC and JHU/APL participation, the common software was funded through the GSFC MO&DA budget. Under the new single-Project management approach, operations funds from MO&DA (institutional support/MOC) and Code S (Mission unique support/ASC, JHU/APL) is vested in one person, the Ground System Project Manager (GSPM) . This allows the GSPM to base decisions on the overall NASA Ground System costs which include the ACE MOC, the ASC, and the ITOCC.

An early, Phase B analysis led to the conclusion that the TPOCC could provide much of the needed functionality in the ITOCC and the ASC as well as the ACE MOC. The Ground Project decided that a generic ACE version of TPOCC, which has subsequently come to be called just ACE Generic, would be developed that would include all functionality common to the ACE MOC, the ITOCC, and the ASC. The ACE Generic would be adapted from the X-ray Timing Explorer (XTE) instantiation of TPOCC since many of the XTE unique capabilities would be useful for ACE. Separate copies of the ACE Generic were then to be augmented individually with capabilities needed variously in the ITOCC, the ACE MOC or the ASC. Most of the MOC unique capabilities are also slated for use in the ASC. A simple Venn diagram depicting this is shown in Figure 1.

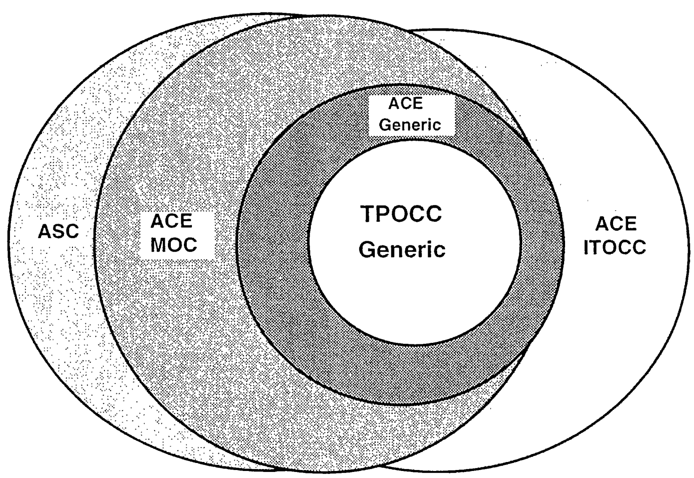

Figure 1. ACE Ground Systems Common Functionality

A natural concomitant to the use of ACE Generic common core of software is to use a common database. Heretofore, it has been accepted procedure for developing multiple databases, one or more for use in developing the spacecraft and integration of the spacecraft and its instruments, another for operations personnel, and yet another or even several more for science operations. This invariably was a source of errors and time lost making corrections and modifying the databases to accommodate data being transferred from one database to another. The ACE Ground Project decided there would be a single database for spacecraft development and testing, for operations, and for science operations. Similarly, the ACE Ground System would utilize the TPOCC System Test and Operations Language (TSTOL) for all procedures and display development. This enables reuse of procedures and displays among the MOC, ITOCC, and the ASC; once developed for spacecraft I&T, procedures and displays can readily be adapted for use in operations, or even for use in the ASC.

4. GROUND SYSTEM DESIGN AND IMPLEMENTATION

Members of the Flight Operations Team (FOT) were included in the Ground Support team from the early phases of the mission. This enabled a smooth transition between spacecraft design and ground operations and avoided the frequently encountered situation where ground operations can be made unnecessarily complicated by spacecraft design decisions. Early FOT support facilitated the multiple use of TPOCC. During development of the ACE Command & Data Handling (C&DH) and its software, members of the FOT were officially stationed at APL to participate in developing and executing test procedures for the C&DH. The FOT also participated in the planned usage and design of the ACE Science Center. Through these activities, the FOT has developed a comprehensive, valuable body of corporate knowledge of the three areas (ASC, Spacecraft I&T, and Mission Operations) that will be carried into operations. The concept of the Integrated Team approach working across spacecraft design, integration and test, and operations has worked successfully on smaller spacecraft, but this is the first time NASA has attempted this approach on a Program of this magnitude. The ability to bring this integrated team into being was greatly aided by vesting the MO&DA and Code S ground budgets under a single GSPM.

TPOCC is designed to be modular thereby enabling upgrading of specific functions or capabilities without requiring that the whole system be redone and retested completely for every upgrade. TPOCC System engineering and development has emphasized software reuse, establishment of separable building blocks, and use of commercial-off-the-shelf (COTS) and government-off-the-shelf (GOTS) products wherever feasible. The TPOCC architecture is characterized by it's distributed processing, conformance to industry standards, and building reusable custom software. TPOCC communications include Ethernet, RS-232, and RS-422. TPOCC adheres to open systems communications standards such as the Transmission Control Protocol/Internet Protocol, external data representation and Network File System. Its user interface includes the X-Window System and the Open Software Foundation MOTIF. TPOCC includes such features as Graphical User Interface, database, development tools, and network management tools. TPOCC has established an extensive library of reusable, generic software components. For ACE, TPOCC libraries have been made portable to PC, SUN, and Silicon Graphics, Inc., and Hewlett Packard (HP) platforms to provide support for instrument GSE systems during spacecraft integration and test and early post launch checkout.

The development of ACE Generic was contracted to Computer Sciences Corporation (CSC) as a task under the MO&DA task order contract. This task also included development of the MOC specific enhancements to ACE Generic. JHU/APL let a separate contract for development of the ITOCC specific enhancements. This contract was let to the same group at CSC responsible for the ACE Generic and MOC development. Many personnel at CSC worked on both the ITOCC and MOC contracts, providing a common contractor for both unique developments. CIT detailed a single person to learn about TPOCC and provide ASC input into the design and development of ACE Generic. This effort required close cooperation between all users and the developers. Questions and decisions concerning design and development of ACE Generic were made at regular Joint Action Development (JAD) sessions augmented by frequent telecons. JHU/APL subsequently enlarged their development team to include personnel supporting the development of the ACE Generic.

For the ACE MOC, some of the ACE Generic was enhancements are:

- Level zero processing,
- Mission Planning and Scheduling,
- Attitude determination,
- Addition of GENSAA —Generalized Systems Analysis Assistant

- Addition of GTAS —Generalized Trend Analysis System.

The ASC will use essentially the same software and hardware systems as the MOC with the addition of the science data analysis software.

For ITOCC, some of the ACE Generic enhancements are:

- Command echo which compares an echoed command with what was transmitted,
- Raw telemetry socket server which sends a telemetry stream via Ethernet to any user,
- GSE commanding enabling ITOCC control of the GSE and collection of its telemetry,
- Spacecraft subsystem run time processing which ensures that certain spacecraft components are run requisite minimum amounts of time and that relays with lifetime limits on the number of state transitions are not over exercised,
- Spacecraft housekeeping trending. This capability is being developed in a TPOCC adjunct system called GTAS (Generalized Trending Analysis System)

HP 748 hosts with multiple processors comprise the core computer hosts for the ITOCC, the ACE MOC, and the ASC. These are augmented with UNIX work stations, HP 715s in the MOC and higher powered HP 735s with more memory in the ITOCC. The MOC HP 748 has an Internet Protocol with its workstations connected to an Ethernet-based local area network. The HP 748 supports mass data storage, as well as additional NASA communications Internet Protocol interface software for receiving spacecraft telemetry data and for sending commands and data to the spacecraft. Figure 2 below shows the ACE MOC and ASC and their relationships with ACE and other entities. Figure 3 depicts the ITOCC and its relation to the spacecraft and ACE MOC.

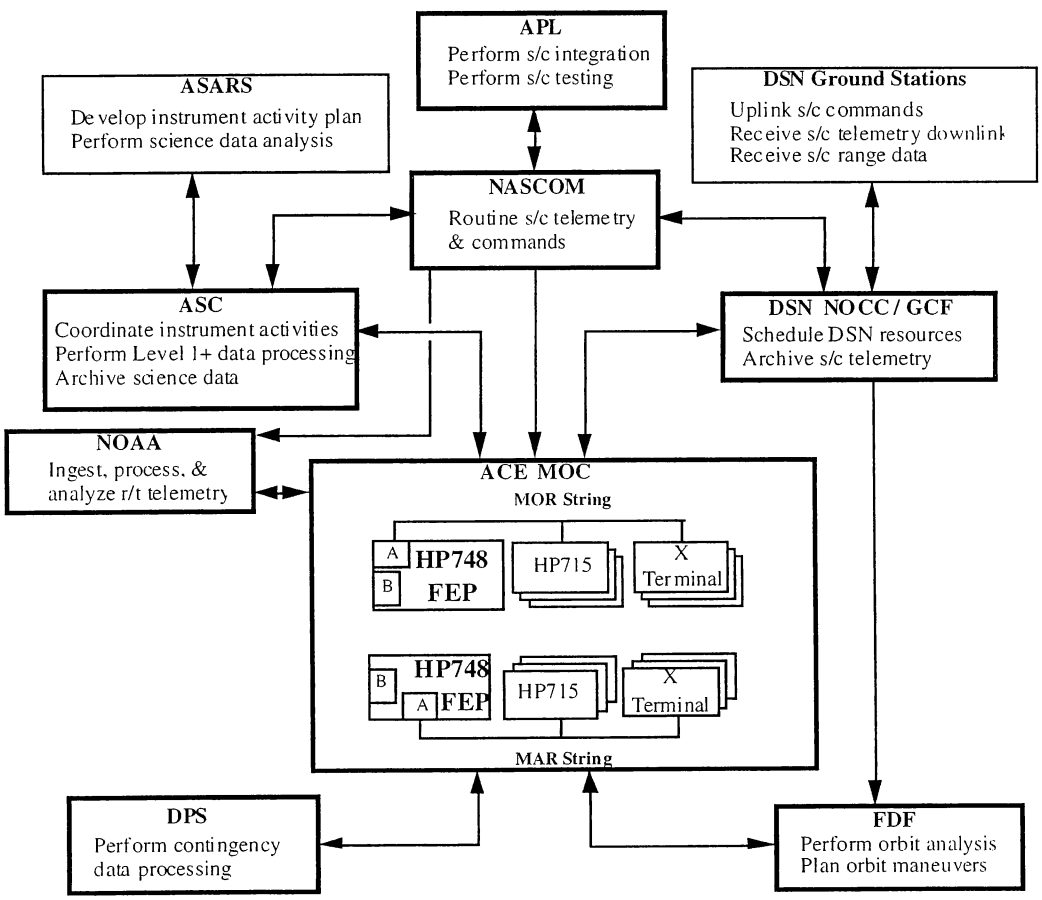

Figure 2. ACE MOC and Its Interfaces with the ASC and other ACE Support Systems

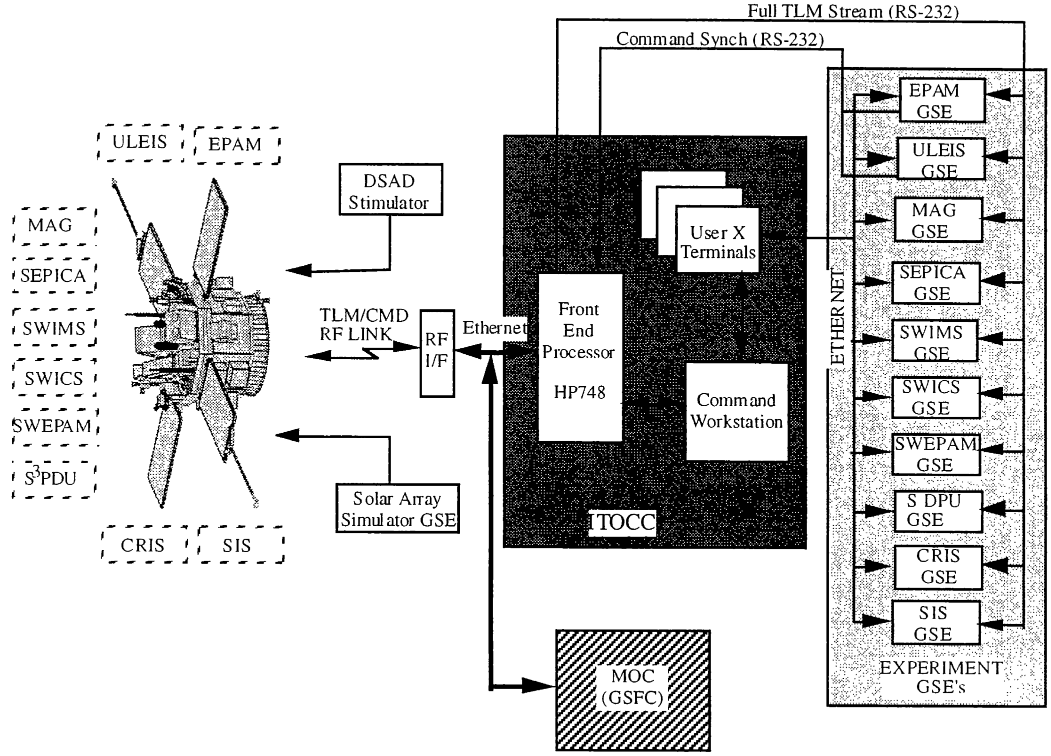

Figure 3. ACE ITOCC

5. BENEFITS

COST REDUCTIONS

SYSTEM DEVELOPMENT

Significant benefits have accrued from multiple use of the ACE Generic system saving NASA millions of dollars. Although the ACE Generic/MOC task required more lines of code than expected for the MOC alone, it was substantially less than the lines of code needed for the three separate systems, the ASC, I&T, and the MOC. Also, the Common Systems between the MOC and spacecraft I&T led to elimination of the training simulator for the FOT. Instead, the FOT is training with the spacecraft at APL. A similar savings in maintenance will be realized; enhancement or correction in one system will enhance or correct all three.

Only one database is utilized for all three systems. This eliminates time consuming, costly translations from one database to another. This also enhances the overall reliability of the content of the database and TSTOL procedures developed for I&T can be adapted easily for use in the ACE MOC and the ASC.

REDUCED FOT

Since the FOT participated in early mission design and spacecraft I&T, the spacecraft functions that affect ground operations (e.g., telemetry, commanding, Star Tracker, Sun Sensors, onboard commands, safing routines, etc.) have been implemented to simplify ground operations with no adverse impact on cost or schedule. This will give us cost savings post launch through a smaller FOT staff. There will be only one shift, seven days per week.

In numerous instances the Ground Project performed trade studies resulting in retention of critical requirements while enabling relaxation of minor requirements. We were able to do this efficiently because the user, the FOT, was involved. In past missions, where the user was not involved, when cost and schedule demands impacted requirements, critical ground requirements would frequently be relaxed necessitating development of operational work arounds and additional software. Such decisions often increased the staff size of the FOT.

The ACE Mission has reduced its costs by $15M in savings. This is in part due to the savings realized in ITOCC and ASC development by using MO&DA software. The ACE Ground Project was able to provide the common ground system to the ITOCC and the ASC without exceeding its original budget..

TRAINING

Significant benefits are accruing in training, because the FOT is being trained using the I&T system and the spacecraft. This training is far more comprehensive than an FOT would normally receive. The FOT is not only learning how to use procedures, but they are actually designing, developing, implementing, and testing the procedures giving the FOT more insight into the procedures and enabling the FOT to respond more quickly to spacecraft anomalies.

When the spacecraft engineers come to GSFC for Launch and Early Operations they will require little additional training since they will already have been working with the TPOCC system. This is also true for the scientists; they will be working with the TPOCC system during I&T and then again during ACE. This reduces the need for multiple simulations and will enable much smoother operations which also reduces budget, schedule, and performance risk.

Decisions have been made on mission requirements and mission goals by the Mission Operations Team which includes the spacecraft I&T team, the ASC, and the MOC personnel. The Mission Operations Team came together early in Phase B. The team has been collaborating for over two years. The confidence in each other's abilities and judgment has built the existing team. With the synergy of the combined team, even though key personnel have left the project, the corporate knowledge within the FOT and the I&T Team have helped train and support new personnel.

6. LESSONS LEARNED

There is a very large overlap between functions performed for spacecraft I&T and the functions performed in operating a spacecraft; however because of the different cultures and approaches between the I&T team and the mission operations team there were some problems understanding requirements. To lessen the impact of these misunderstandings, many meetings were needed between the I&T team and the software developers. One critical problem was the different priorities affecting the schedule. Another problem was the different approach for managing schedule reserve. Mission Operations Center development at GSFC has tended to vest schedule reserve in the ability to accommodate a schedule slip or failure of a function by postponing work to future releases. However, delays of this scale cannot be accommodated when building an I&T system. Schedule reserve for unforeseen work must be included in the basic schedule for an I&T system just as it is for any spacecraft component or instrument.

The attempt to reuse functionality from the XTE instantiation of TPOCC proved to be a mixed blessing. While the reuse of the XTE software reduced costs, the lack of control over the XTE software development schedule increased ACE schedule risk. The XTE system was less mature than expected and its use became a source of errors in the ACE Generic. Similarly, we had expected to use the GTAS for trend analysis in the ITOCC. It too proved to lack needed maturity and contained enough errors so that its use in the ITOCC was dropped. We do plan to use a more mature version of GTAS in the MOC. We concluded that to be the first user of GOTS or COTS, may not be worth the additional schedule risk, especially when you have hard deadlines that cannot accommodate extensive system debugging.

7. CONCLUSION

The fixed cost imposed by NASA for the development, implementation, testing, and operation of the ACE ground system and the challenge of "faster, better, cheaper" led the ACE Ground Project to adopt a common ground system architecture to support observatory integration and testing, flight operations, and science analysis. Existing software, such as TPOCC, and COTS products were employed wherever applicable. A significant factor in the success of this approach was the very early, Phase B involvement of the FOT in system engineering from spacecraft design, through spacecraft I&T to the mission operations. Another major factor in the success of this approach was the close cooperation of the FOT, JHU/APL, CIT, and GSFC personnel and the cooperation of the contractor, CSC. The common ground system resulted in substantially reduced development costs, expected future savings in sustaining engineering, and more comprehensive training for the FOT.

Reference:

Snow, Frank et al; " Management Approach for Reducing the Life-Cycle Costs of the ACE Ground System; *Proceedings of the 1st International Symposium on "Reducing the cost of Spacecraft Ground Systems and Operations*"; September, 1995