PERGAMON

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Acta Astronautica 52 (2003) 337–342

ACTA ASTRONAUTICA

www.elsevier.com/locate/actaastro

Trends in cost-effective mission operations

Jozef van der Ha[1]

10001 Windstream Drive # 706, Columbia, MD 21044, USA

Abstract

The pressure on achieving cost reductions in Mission Operations has been increasing steadily during the past decade and there is no relaxation in sight for the near future. Therefore, it is necessary to scrutinize mission design and operations concepts for potential in achieving still better cost effectiveness. The present paper presents an assessment of a few concepts that are expected to be promising for further increasing the cost effectiveness of future space mission operations, namely: on-board spacecraft autonomy and on-ground automation, commercial off-the-shelf control systems, multi-mission operation concepts, and hibernation modes. The latter concept is of specific relevance to interplanetary spacecraft with long cruise phases.

1. Introduction

It is safe to predict that the pressure on achieving cost reductions in space missions will not relax within the foreseeable future. Therefore, space mission design, spacecraft design, and operations concepts must constantly be scrutinized for additional reductions in overall mission cost.

In order to accomplish meaningful design and cost trades the mission operations concept must be established as an integral part of the overall mission system design process incorporating all mission elements. Within such an integrated design philosophy the most cost-effective operations concept (along with the design concepts of the other system elements) will evolve in a natural manner [1]. This methodology allows the achievement of an *overall life-cycle cost effectiveness* that cuts across the traditional barriers between mission design, spacecraft design, ground system design, and mission operations.

The progress in lowering mission operations costs achieved over the past 5–10 years is without any doubt very impressive. This has been brought about mainly by the execution of the following concepts: on-board autonomy, automation of routine spacecraft monitoring and control functions, standardization of telemetry and command interfaces, and re-use of hardware and software facilities from one satellite to the next and between spacecraft test and operations phases.

Notwithstanding the significant progress made already, there certainly exists potential for future cost reductions offered, for example, by further enhancements in on-board autonomy and on-ground automation, by implementing commercial off-the-shelf control systems and multi-mission operations, and by the use of hibernation modes.

2. Past progress

Enormous progress has been made during the last 5 or so years in reducing space mission costs in general

---

[1] Consultant, Mission Design & Operations.
E-mail address: jvdha@aol.com (J. van der Ha).

0094-5765/03/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0094-5765(02)00173-X

and operations costs in particular as documented by the pertinent books [2,3] and in the papers presented in the symposia addressing low-cost themes. Progress can best be seen and understood when looking back at some of the main issues that were being discussed some 4 years ago [1]. It may be concluded that most of the concepts that appeared somewhat ‘revolutionary’ and ‘uncomfortable’ at the time are now generally accepted as ‘self-evident’ and ‘common-sense’, in particular:

1. *Short implementation schedule*: At present, a 3-year implementation schedule is ‘almost routine’ for many of the interplanetary missions (in particular, NASA’s discovery series).
2. *Mission system engineering*: The awareness that design trades and decisions need to take account of all relevant system elements in order to achieve meaningful cost-effectiveness is now widespread.
3. *Full system and full lifetime cost accounting*: This practice has now been adopted by virtually all players and has helped to improve our understanding of the nature and distribution of mission costs.
4. *Empowered team*: It is now a ‘fait accompli’ that empowerment and commitment of the team doing the actual hard work is a necessary condition for an effective fast-track mission implementation.
5. *Autonomy and automation*: Although progress in this area has perhaps been somewhat slower than foreseen little doubt remains about feasibility, usefulness and cost-effectiveness of these concepts.
6. *Test and operations commonality*: It is now generally recognized that the implementation and maintenance of two separate systems for supporting spacecraft tests and for mission operations is not cost-effective nor necessary.
7. *Use of existing and off-the-shelf elements*: Cost pressures have lead to consideration of these strategies but complete implementation of both concepts lies still ahead.
8. *Concurrent engineering and rapid prototyping*: These implementation processes are more commonly used now than in the past, mainly by necessity (as there is no alternative when facing a 3-year approval-to-launch schedule!).

3. Autonomous operations

3.1. Evolution of operations team sizes

In the past, satellites operations involved very large teams of specialized engineers and well-trained operators working around-the-clock to interpret telemetry data, to monitor and evaluate the performance of every subsystem and instrument on-board, to prepare telecommand up-links, and to detect and correct any problems that would occur.

It is of interest to compare the evolution in the size of operations teams for past and present interplanetary missions [4]. The Mars Viking mission control team in 1976 had as many as 400 staff, while the 1989 –1994 Magellan Venus radar mapping mission used a team of about 70 controllers at the time of its critical orbit insertion. Later in the 1990s the Mars Global Surveyor had a maximum of 28 controllers during its aero-braking phase. A team of 21 staff operates the NEAR spacecraft during its critical (asteroid orbit insertion) phase. The CONTOUR (comet nucleus tour) spacecraft is planned to have a maximum operations team of six people during its most critical phases [5]. Fig. 1 provides a visualization of the dramatic reduction in operations workforce during the last decades.

These enormous reductions in operations staffing have been made possible mainly through the extended use of on-board autonomy and automation of the on-ground monitor and control facilities. It should not be overlooked, however, that there has also been

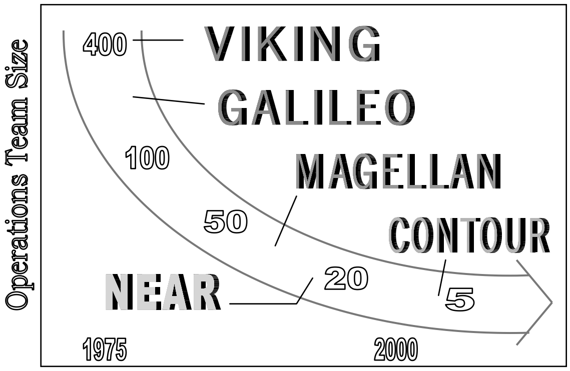

Fig. 1. Evolution of interplanetary missions operations teams sizes.

a profound evolution in operations ‘philosophy’: in the past, it was a common practice to monitor spacecraft by at least one person around the clock. This was especially true for interplanetary missions even though a close-to-real-time reaction was not feasible due to the long propagation delays.

Nowadays, continuous monitoring has become not only unaffordable and unachievable (because of limitations in the Deep Space Network’s capabilities) but, in fact, it is also not anymore considered a necessity. In many cases, a human operator is alerted only after the on-board or on-ground logic have autonomously detected and identified anomalies.

3.2. Autonomy versus human operators

One of the most significant past (as well as future!) trends in spacecraft system design is the tremendous growth in on-board processing power and memory storage capabilities. This means that many of the traditional ground functions can now be performed autonomously by the on-board processor: in particular, the routine spacecraft monitoring and control functions can be migrated to the on-board autonomy and, in fact, this is often done nowadays. The on-board processor can perform resource management tasks (in particular, memory and power allocation) very effectively since it has instantaneous access to the relevant input parameters [6].

Instead of relying on on-board autonomy preference may be given to the automation of the on-ground monitoring and control process as this option is usually (rightly or wrongly?) perceived as less risky. In any case, it is generally accepted that the use of standardized and validated command sequences instead of the manual preparation of individual commands is beneficial for reducing the likelihood of errors.

Although automation may not completely eliminate the possibility of human errors in all circumstances there is little doubt that it has considerable potential in inhibiting a number of specific human shortcomings (like lack of concentration). Automation usually results in an enhancement of the reliability of repetitive operations procedures in addition to its significant cost advantages.

Whereas autonomy and automation have considerable advantages during ‘routine’ operations, it remains true that the resolution of complicated anomalies as well as recovery from contingencies still depend on the unique reasoning capabilities of a human operator and this is unlikely to change anytime soon.

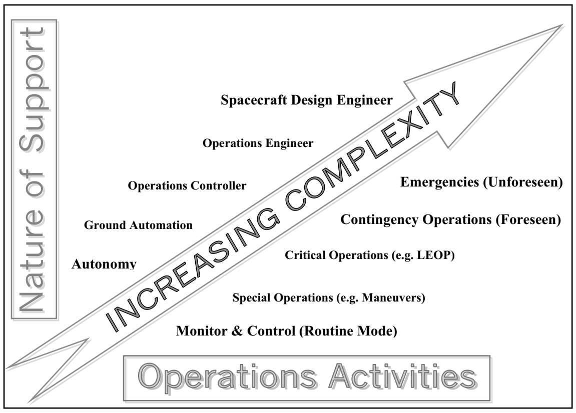

Fig. 2. Hierarchy of operations activities and corresponding support.

Figure 2 provides a visualization of the ‘hierarchy’ of operations control activities and an indication of the associated support concepts most commonly used nowadays. The operations cost will naturally increase in proportion to the complexity of the operations activities required. On the other hand, the phases of the more critical operational activities are relatively short in general.

4. Commercial off-the-shelf systems

4.1. Control systems

The recent trend towards commercial off-the-shelf (COTS) control systems has been stimulated by the emergence of satellite constellations (mainly for tele-communications applications) which require cost-effective multi-satellite control systems at different sites. A number of private companies are now active in the market for mission-dedicated control systems based on generic software platforms, for instance (in alphabetical order):

- Altair Aerospace, Bowie (MD): Altairis software system.
- Exigent International Software Technology Inc. (STI) of Melbourne (FL): OS/Comet.

- Integral Systems, Inc. (ISI) of Lanham (MD): Epoch 2000 system.
- Interface & Control Systems (ICS) of Melbourne (FL): SCL software.
- L-3 Storm Control Systems of Herndon (VA): Intelligent Mission Toolkit (IMT).
- Lockheed Martin Missions System of Gaithersburg (MD): SCS 21 control system.
- Raytheon System Space Systems Unit of Denver (CO): Eclipse & Perigee systems.

Prices and delivery schedules will continue to decrease because of the continuously improving ‘economy of scales’. At present, the price for a COTS system ‘without bells and whistles’ has come down to as low as 25 K$ for the support of a simple university-class small satellite. The delivery (including integration) schedule of a relatively standard control system is in general not more than 3–6 months.

There exists no completely off-the-shelf product that will be able to fly any new satellite without customization since each satellite is unique. The use of COTS software has often demanded a considerable amount of customization effort in the past: the increasing experience of the software suppliers will likely lead to improvements in this respect. Instead of customizing the software code the spacecraft-specific information is usually placed on a database: this lowers the implementation cost and facilitates maintenance.

The modern systems not only cost much less to implement and to operate than their previous generations they are also more ‘robust’ to hardware and software problems. Automation is inherent to the point that an operator will be alerted only if a situation is encountered which was not foreseen in its design. The systems are designed on the basis of generic, reusable software elements that incorporate the hard-earned expert knowledge gathered in past operations. They offer considerable potential for further reductions in the operations team sizes of the future.

A few of the present low-cost interplanetary missions are participating in this trend: in particular, the control systems (for spacecraft testing as well as in-orbit operations) for APL’s Discovery missions NEAR and CONTOUR missions have been built on the commercial Epoch 2000 system.

4.2. Other COTS facilities

An interesting recent trend is the possibility of leasing a complete COTS ground system, including ground station and communications network for a certain period of time. For instance, Honeywell Technology Solutions Inc. (previously, AlliedSignal Technical Services Corp.) of Columbia (MD) offers a complete set of ground system elements that can be leased by interested customers for the support of any type of mission. This ‘DataLynx’ system [7] contains the full suite of ground facilities (including worldwide ground station and data network facilities as well as a fully equipped control center), operators, and the associated support functions like mission planning and scheduling, monitoring and control, data processing and distribution. Exigent International has provided most of the software and hardware elements for this system.

The increasing availability of ‘niche’ commercial software products may also be mentioned in this context: they provide specific support functions for instance in the areas of mission design, mission analysis, and performance evaluation. A well-known example of this trend is the mission analysis software contained in the so-called Satellite Tool Kit (STK) marketed by Analytical Graphics, Inc.

An interesting example in the area of spacecraft performance monitoring is the ‘TowerView’ software [8] marketed by High Tower Software of Irvine (CA). TowerView is a sophisticated software capability that was originally developed at JPL and is still (in previous generations) being used in NASA JPL’s Voyager, Galileo, and Cassini operations. The product gives users immediate access to thousands of satellite health parameters with a single mouse-click. Towerview shows basic health parameters for any number of satellites or more detailed data for an individual satellite on a single screen. The software is particularly effective for identifying out-of-limits data and for providing a quick visualization of the nature and the severity of the observed anomalies.

4.3. Advantages of COTS systems

The most significant advantages of using a COTS product may be summarized as follows:

Cost-effectiveness: The cost of implementing and using a COTS system is obviously significantly lower than that of a dedicated newly developed system. In fact, a COTS system will likely be cheaper than a system resulting from the 'enhancement' of existing in-house capabilities as well. This is due to the fact that almost always significant difficulties are encountered when altering and customizing systems that have not (or not well enough) been designed a priori to accommodate future upgrades.

Implementation and test schedule: Because of their relatively extensive experience in implementing, integrating, customizing, and testing of control systems COTS system providers are more likely to meet short (and strict!) schedule deadlines.

System reliability: A long heritage in many types of applications translates into a large number and a wide variety of debugging opportunities: this eventually reflects in a higher reliability and stability of the resulting system.

5. Multi-mission operations

An obvious strategy for reducing mission operations costs is by using the same facilities and teams for a number of missions. This is common practice in the tele-communications business where an operator organization typically has a whole fleet of satellites to look after. In the case of interplanetary missions the mission frequency is much lower so the opportunities for multi-mission operations are more rare.

Opportunities exist often to combine interplanetary spacecraft with other types of missions as was done for instance at ESA/ESOC during the GIOTTO mission when many of its support facilities as well as operations staff were being shared with other (science, tele-communications, and Earth observation) missions. At NASA/GSFC the control center facilities of the SOHO mission are being shared with the ACE mission.

Multi-mission operations concepts offer significant advantages in terms of the efficient utilization of staff and facility resources because of the greater flexibility in combining and distributing the necessary supporting activities. As a result, a team of not more than 20–30 operators would be able to support a fleet of 4–5 present-day interplanetary missions in a 'shared mode'. Lockheed Martin Astronautics had planned [4] such a size team to control three Mars missions along with the Stardust and Genesis discovery missions.

In the near future, APL will have the opportunity to take advantage of the multi-mission support concept through the 'simultaneous' operations of the CONTOUR and MESSENGER discovery missions (although not more than one mission will actually be controlled actively at any given instant of time).

6. Hibernation mode

A less common but uniquely powerful method for reducing mission operations costs is by using a so-called hibernation mode during which the spacecraft is 'dormant' and survives for an extended period of time without any operations support from ground whatsoever. This concept is of particular interest for interplanetary missions having long cruise phases without science activities. Hibernation has been used a few times in the past: for instance, ESA's GIOTTO spacecraft was put into hibernation [9] after its Halley comet encounter for a period of close to 4 years and again after its Earth flyby for another 2 years leading up to the Grigg-Skjellerup comet flyby. The GIOTTO hibernation strategy was actually an 'afterthought' since it could hardly be expected that it would be capable of 'surviving' the close Halley flyby.

APL's CONTOUR mission has been designed from the outset with at least six hibernation periods of up to 7.5 months duration between its Earth flyby's and comet encounters [5]. In fact, more than 60% of its nominal mission lifetime will be spent in hibernation! During these hibernation periods almost all of the spacecraft units will be switched off except for the power subsystem, heaters, and command receivers which will be kept switched on. A single command system will perform a limited number of monitoring and control functions (in particular, to guarantee adequate battery charging and thermal conditions) by means of simple autonomy rules.

Whereas CONTOUR will use a three-axis mode during its comet encounters, it will be spin stabilized (between 10 and 20 rpm) during hibernation. The stability of the spin axis pointing orientation relative to the orbit normal direction will be better than 15°

(including dynamic balance effects). It may be stated that, in general, the design of an hibernation mode requires the use of spin stabilization: this mode provides adequate pointing stability without any active monitoring and control. It would be extremely cumbersome and costly to design an autonomous three-axes control strategy that would be able to guarantee the spacecraft's safety during all possible conditions (and failures!) over an extended interval of many months.

Although hibernation periods themselves do not demand operations support, the implementation of a hibernation strategy has considerable repercussions in terms of operations concept [5]. In particular, maintaining (or re-acquiring) an adequate spacecraft and operations expertise during long hibernation periods is not a trivial exercise. It implies that more effort must be allocated to documentation tasks and training courses. This issue becomes even more compelling in cases where experienced operations staff can not temporarily be 'parked' in other suitable jobs. Under these circumstances it may become attractive to hire suitable (in particular, those experienced in similar jobs on other missions) staff from outsourcing companies.

References

[1] J.C. van der Ha, M.H. Marshall, J.A. Landshof, Cost-effective mission operations, Acta Astronautica 39(1–4) (1996) 61–70.

[2] J.R. Wertz, W.J. Larson (Eds.), Reducing Space Mission Costs, Microcosm, Inc. & Kluwer Academic Publishers, Dordrecht, 1996 (Chapter 6).

[3] D.G. Boden, W.J. Larson (Eds.), Cost-Effective Space Mission Operations, McGraw-Hill Inc., New York, 1996.

[4] A. Eisele, Mission control downsized for new era, Space News 9(16) (1998) 4.

[5] H.E. Holdridge, Applying successful operations approaches developed for NEAR and refining for CONTOUR mission implementation Acta Astronautica, this issue, PII: S0094-5765(02)00174-1.

[6] S. Lee, A. Santo, Contributions of spacecraft autonomy to low cost mission operations: the Near Earth Asteroid Rendezvous (NEAR) experience, Presented at the 48th IAF Congress, Turin, Italy, October 6–10, 1997, Paper IAA.11.3.002.

[7] T. Sorensen, T. Probert, DataLynx: a Commercial TT& C and mission operations service for low-cost planetary missions, Proceedings of the Fourth IAA International Conference on Low-Cost Planetary Missions, JHU Applied Physics Laboratory, MD, USA, May 2000, Paper IAA-2000-0806.

[8] J. Bates, NASA-developed software aids commercial operators, Space News 11(9) (2000) 15.

[9] H.R. Nye, A. Morani, The GIOTTO extended mission (GEM)—high risk, high payoff, ESA Bulletin, No. 73, February 1993, pp 32–41.