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TRANS-GLOBAL MISSION ARCHITECTURES

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ABSTRACT. Operations includes the utilization of both space and ground resources to achieve mission objectives. Architectures of the future must also apply to both space and ground components to create a mission architecture. In reality the "global" view will become too small! The next generation will make the spacecraft a node on a distributed system, expanding the scope of missions beyond the merely global. Design, development and operation of the spacecraft and operations to a single operational concept derived from the mission objectives will create a virtual presence of the investigator on the spacecraft and instruments.

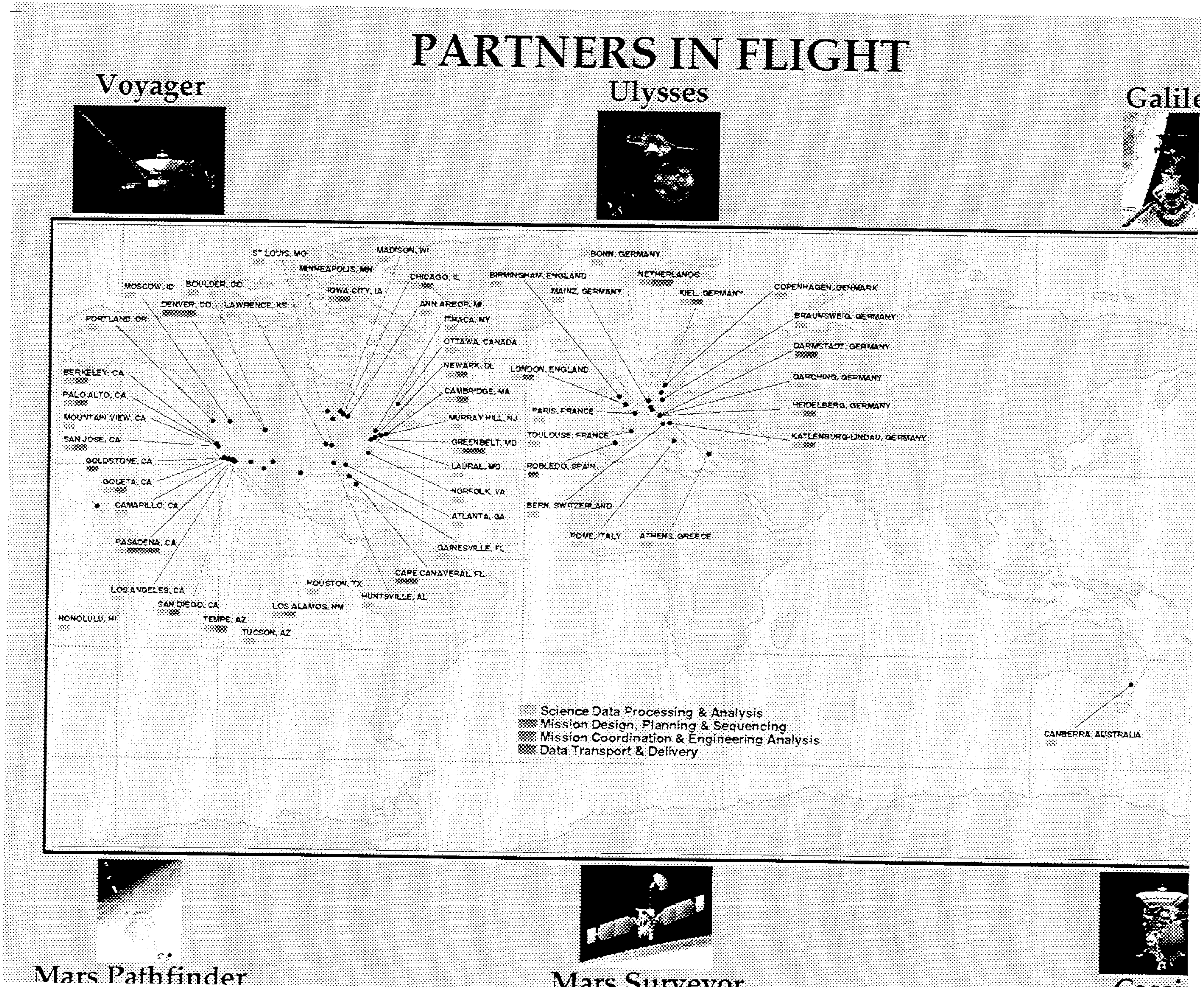
1. Evolution of Planetary Mission Operations

In the early days of space exploration, the cost of missions was driven largely by the spacecraft development cost. Mission operations costs were driven by the high cost of computing resource in the form of mainframe computers. Electronic communications, like the software for a mission was complex and costly, developed as a custom implementation specifically for each new mission. There were few missions, widely separated in lime, with new mission operations systems created for each mission to optimize the return from the spacecraft. Mission operations teams tended to be centrally located near the computers in an operations center. Command and control of the spacecraft *was* accomplished only from this center, where the coordination of science and engineering demands on the spacecraft and instruments occurred during a long-duration series of reviews. Inclusion of scientee and engineering experts from remote locations and other countries was severely hampered by long time delays in exchange of information. Scientists not located near the center were likely to experience long delays in the delivery of the data from their instruments. During major mission events, scientists would relocate temporarily to the operations center.

Large numbers of people were involved in the daily monitoring of the spacecraft, in dealing, with anomalies, and in offsetting any deficiencies in operational response of the spacecraft. The use of such innovative and dedicated people was effective in obtaining maximum use of the expensive spacecraft resource, but the cost was high. As missions increased in length for planetary exploration, the mission operations costs over the life of the mission often exceeded the cost of development.

The evolution in the 1980's of lower cost high-performance compute power and affordable high-bandwidth communications dramatically expanded the partnering involved in large missions. The inclusion of geographically distributed teams as an integral element of mission operations was enabled by the integrated distributed information systems and the client-server architectures. Both local and remote engineering and science elements became active participants in daily mission operations. In addition to the electronic transmission of data, mission such as Magellan in the 1980's operated successfully with a team of engineers provided at the spacecraft contractor site in Denver linked electronically to the mission control center in Pasadena and using replicated hardware and software. For Mars Observer project, Science Operations Planning Center (SOPC) systems were remotely located at science investigator home locations to allow noninteractive commands to be prepared and electronically delivered for automatic integration into the spacecraft command sequence. The inclusion of science investigators as integral members of mission operations reduced **overhead** in operations and provided more timely response to investigation requirements. New missions of'the 1990's such as Cassini and the Mars Surveyor series take advantage of the remote integrated teams with smaller and fewer mission operations teams in highly challenging science missions. Even traditional missions such as Voyager and Galileo have adapted their mode of operat ions "on the fly" during their MO&DA periods to provide added online data access and d~'lively for their user community while reducing the cost of'operations. Missions now routinely employ university, industry, and government agency expertise from all parts of the country, and from around the world. The extent of' this involvement in planetary mission development and operations is illustrated in figure 1, "Global Involvement in Planetary Missions in the 1990's". In addition, the advent and widespread use of the Internet allows the neartime sharing of mission status, results and products not only with the small number of scientists closely aligned with the mission, but with the broader community of investigators and indeed with primary and secondary educational institutions and with the general public. The interest and satisfaction generated by this access is indicated by more than 2 million visits to the Galileo pages during the period from Jupiter orbit insertion through Ganymede encounter. To facilitate access, graphical and text-bawd user interfaces are provided.

Figure 1. "Global Involvement in Planetary Missions in the 1990's'"



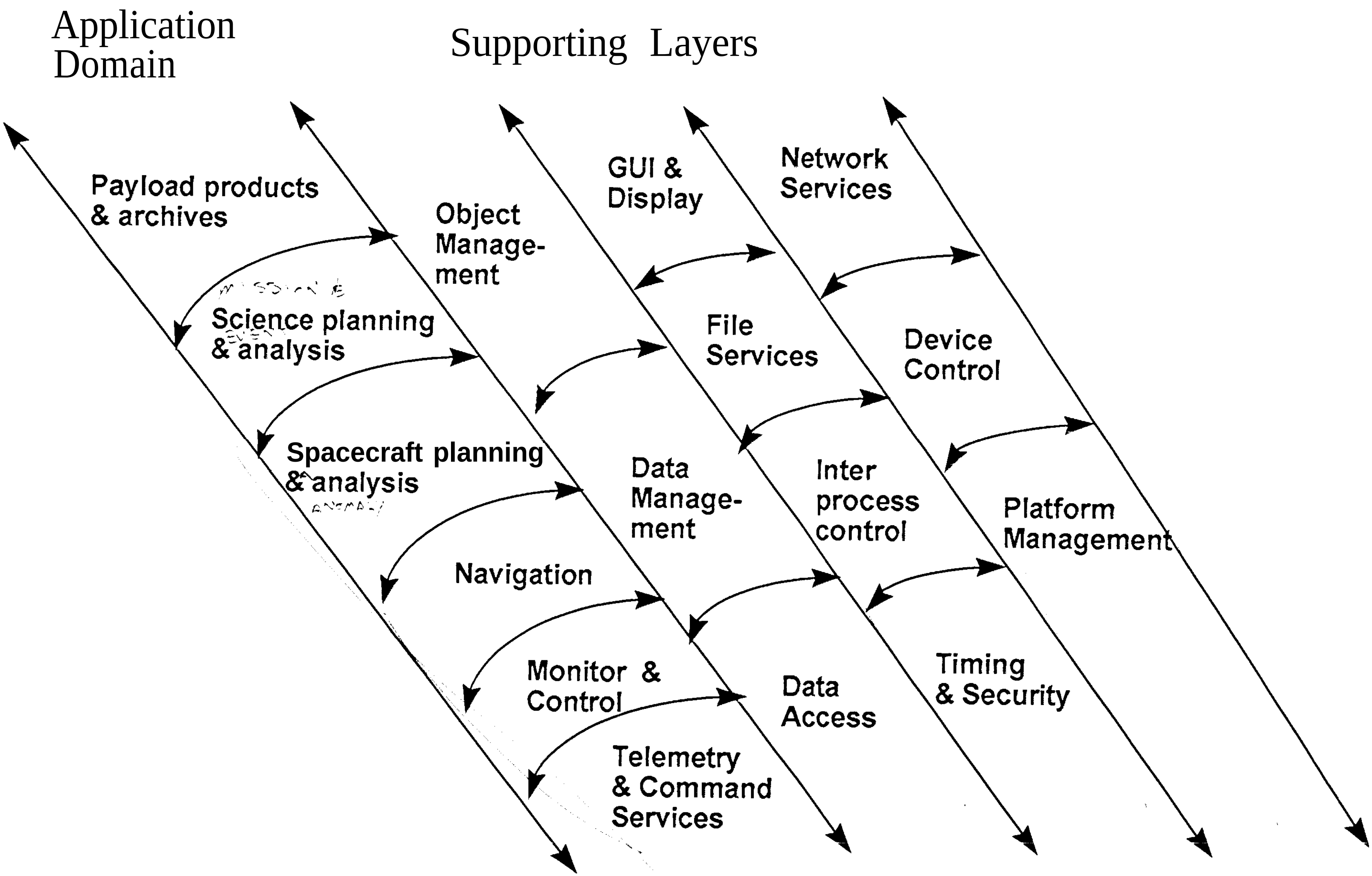
PARTNERS IN FLIGHT
Voyager
Ulysses
Galile
ST LOUIS, MO
MADISON, WI
MINNEAPOLIS, MN
IOWA CITY, IA
CHICAGO, IL
MOSCOW, ID
BOULDER, CO
DENVER, CO
LAWRENCE, KS
PORTLAND, OR
ANN ARBOR, MI
ITHACA, NY
OTTAWA, CANADA
NEWARK, DL
CAMBRIDGE, MA
MURRAY HILL, NJ
GREENBELT, MD
LAUREL, MD
NORFOLK, VA
ATLANTA, GA
GAINESVILLE, FL
CAPE CANAVERAL, FL
HOUSTON, TX
HUNTSVILLE, AL
LOS ALAMOS, NM
TUCSON, AZ
TEMPE, AZ
SAN DIEGO, CA
LOS ANGELES, CA
HONOLULU, HI
PASADENA, CA
CAMARILLO, CA
GOLETA, CA
GOLDSTONE, CA
SAN JOSE, CA
MOUNTAIN VIEW, CA
PALO ALTO, CA
BERKELEY, CA
BONN, GERMANY
BIRMINGHAM, ENGLAND
NETHERLANDS
MAINZ, GERMANY
KIEL, GERMANY
COPENHAGEN, DENMARK
BRAUNSWEIG, GERMANY
DARMSTADT, GERMANY
GARCHING, GERMANY
HEIDELBERG, GERMANY
KATLENBURG-LINDAU, GERMANY
LONDON, ENGLAND
PARIS, FRANCE
TOULOUSE, FRANCE
ROBLEDO, SPAIN
BERN, SWITZERLAND
ROME, ITALY
ATHENS, GREECE
CANBERRA, AUSTRALIA
Science Data Processing & Analysis
Mission Design, Planning & Sequencing
Mission Coordination & Engineering Analysis
Data Transport & Delivery
Mars Pathfinder
Mars Surveyor
Cassi

2. Modularity and Re-use in Ground Data Systems

Broader and more distributed involvement in mission operations, however, did not change the number of people involved in mission operations or reduce the cost. Software standards, high level languages and relatively low cost high-performance engineering workstations decreased the cost of mission operations development. Additional software required for the management of increasingly complex spacecraft has often more than offset the savings. Software and people replaced hardware as the dominant cost in both development and operations of space missions. The next major step in reducing the mission operations development cost was the reuse of software applications. The efficacy of this approach is enhanced by the use of space data system standards and by a modular architecture with common interfaces among functional elements. Use of standard operating systems and platform-independent implementation allows the re-use of major software developments such as navigation and planning, software on new hardware platforms for new missions and for replacement of aging systems during the operational life of long-flight missions such as Voyager. There is typically a somwhat higher cost for the initial development of re-useable systems, called multimission systems at JPL, but experience has shown the "break even" point for multimission systems to be at less than two missions. The effort to apply re-useable systems to new missions varies from table definitions for typical telemetry functions to the addition of models for new mission components for sequence validation and analysis functions. The modularity of the multimission system allows the integration of re-used elements and project-unique elements to create a project's mission operations system. This flexibility allows a common set of multimission software to yield 95% of the ground data system for the large Cassini mission, but also to provide 95% of the support for the small Mars Pathfinder mission at less than 20% of the normal development cost for such a mission. Capability-driven design based on the availability of ground systems for both spacecraft development and operations and concurrent design trades between spacecraft and ground systems have evolved as the preferred method to reduce development costs for the mission system as an entity. In addition to the modularity of the domain applications unique to mission operations, a layering of support functions with the operational environment has been employed, as illustrated in figure 2, "Layered Architectures in Multimission Operations Systems". The layering of the application fucntions is a direct extension of the concept employed in the ISO Communications model. Support and application functions and their interfaces are standardized.

Figure ?, "Layered Architectures in Multimission Operations Systems"

Layered Mission Operations Architecture



Changes currently underway will extend the multimission system by deploying existing software modules in a "plug and play" architecture to allow selection of needed functions, all with common external and internal interfaces and formats, and to allow the easy integration of new functions from technology development, industry and commercial sources, or from any collaborating partner in mission operations. In operation, all functions required for any mission functions will be accessible from a single workstation, local, remote or mobile. The combination of formatting, presentation and tools will allow a single person to operate many functions as a "system" expert and to access detailed tools within the domain expertise without the need for extensive training in tools. The integrtion of public institutions into mission operations is quite feasible for some missions, providing not just feedback, but active participation of the expanded communities of scientists as well as the ultimate customers, the taxpaying public.

The combination of modularity and layering of the functions used in multimission re-useable ground systems has allowed the use of commercial systems for in the supporting layer for functions including data management, graphical user interfaces and platform environment management functions. An increasing commonality between communications, military and scientific satellites has also promoted the availability of commercial, easily configured systems for some telemetry acquisition and command functions. Interoperability and commonality of distributed systems utilizing standards and standard architectures will make possible the flexible and even dynamic integration of NASA, industry, university and DoD resources in the fulfillment of mission objectives. The extensive re-use of software does much to reduce the development and software maintenance costs for mission operations. It does not, however, directly reduce the staffing costs for operations, now a major limiting factor in the affordability of space exploration. Interoperability offers one possible solution to further reductions. The other potential solution now practiced is the use of automation and autonomy.

3. Automation and Autonomy

As noted earlier, the cost of people has become the dominant factor in mission operations. Long-duration mission typical of planetary exploration combined to produce very high operations costs. Automation through specialized software, while costly to develop and test, became a necessity for affordable missions. The trend and demand is to reduce or eliminate operations for routine functions, and to focus human operations attention to events and anomalies of the mission including calibration, spacecraft emergencies, and the ultimate adventure of unmanned exploration, the science observation and discovery. Automated software can scan telemetry for static or trend anomalies, or apply data mining techniques to identify derived events. Analysis tools, sometimes using artificial intelligence and fuzzy logic are employed today in ground-based systems to aid the analysis of identified events and determine or recommend corrective actions. The safety of the spacecraft and its observations with less human attention has been the subject of concern. As planetary exploration moved beyond the inner planets, however, the increase in round-trip light time from a few minutes to hours precluded the early practice of real-time commanding. To avert fatal damage to spacecraft before ground operators could intervene, autonomy was introduced into control computers on planetary spacecraft to "safe" the spacecraft from irreparable damage while awaiting human intervention. Reliance on the safety of the spacecraft has encourage the development of operational concepts which emphasize prime shift only operations rather than round-the-clock "real-time" monitor and control of the spacecraft. The use of autonomy on board the spacecraft is now being developed to enable functions which require more immediate response than a remote human can provide, for example direct orbit insertion or landing and movement on remote bodies. Onboard autonomy can also be used to orient the spacecraft and instrument for scientific observations. Optical navigation with ground and spacecraft elements was used for Galileo. The use of autonomous maneuver and navigation for future spacecraft will allow longer periods between human intervention. The evolution to smaller spacecraft with more flight opportunities overstresses the capacity of the Deep Space Network (DSN). Longer periods between contacts decreases the loading demands on the DSN. Greater ability for the spacecraft to self-monitor, and self-plan is also required during the longer periods between attention. Additional techniques are under development to reduce demand for routine scheduling of ground tracking. Early uses of onboard autonomy, however, created additional workloads for operations. The concept of spacecraft "operability" was introduced. The design of spacecraft for operability and for effective use of existing capabilities requires the participation of both spacecraft/instrument and mission operations engineers with science and mission planners from the very beginning of mission concept development.

4. Trans-Global Mission Architecture

'The experience in layering of system functions and re-useable components which has proven itself in the ground system world can now be applied to the spacecraft flight control software and avionics as well. As the mission information system is designed and implemented, the spacecraft with its autonomy and control functions becomes a node on the end-to-end information system. The mission operations system now encompasses both space and ground components, meriting the name "trans-global mission architecture". Figure 3, "Trans-global Mission Architecture", shows this extension of the layered re-useable mission operations architecture to create an open grtmnd/space operations system. 'The service layer provides a support environment for spacecraft functions, which in turn act a suport layer for instruments. The open standards, as in previous experience, will allow the use of one of a set of alternative components for each function, selected to meet the needs of different classes of missions. Unique components required for specific needs such as deep space may be be combined with functions such telemetry management common among communications satellites, earth explorers and planetary explorers to reduce the cost and the lime delays in implementation.

Figure 3, "Trans-global Mission Architecture"

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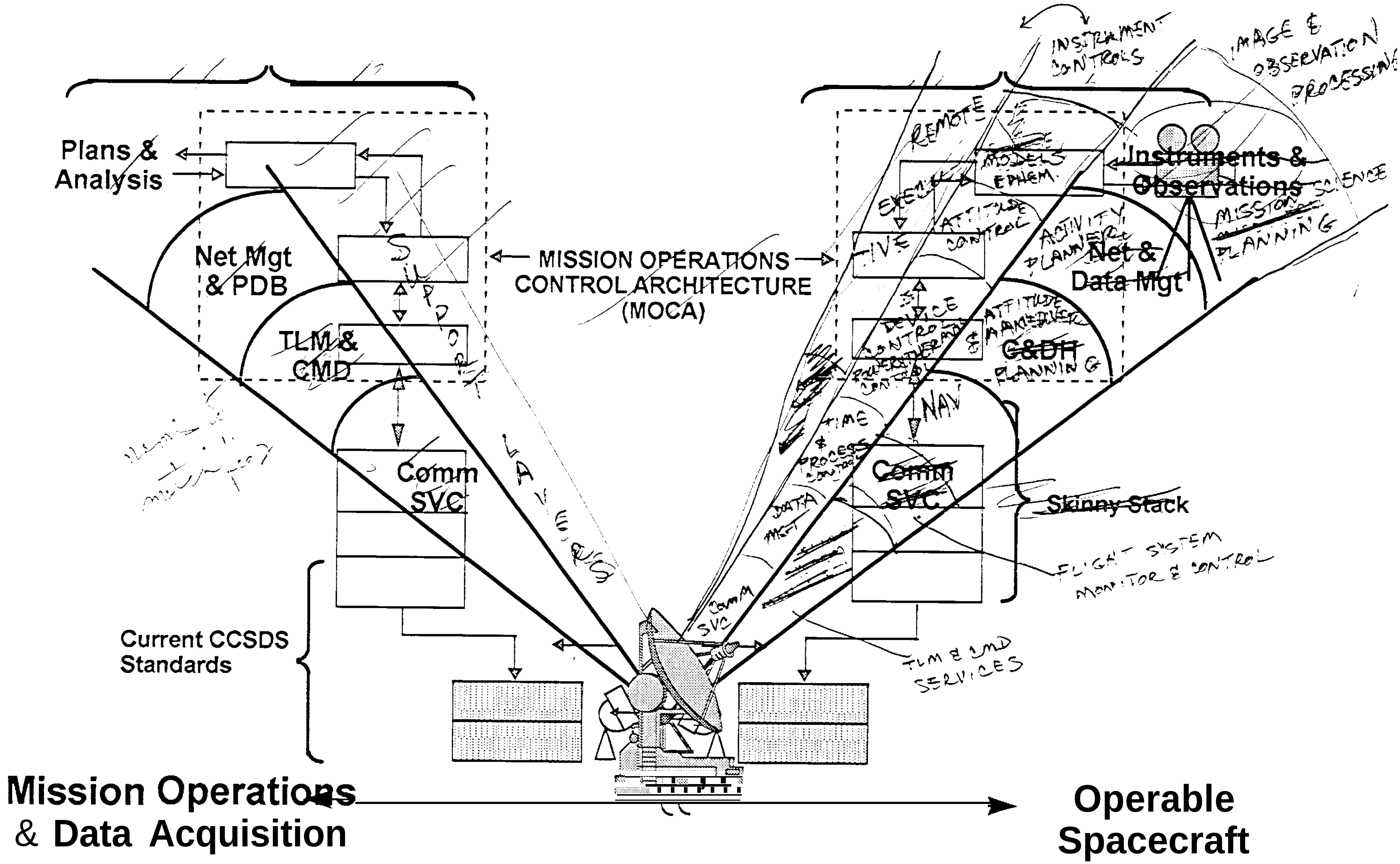
Open Ground / Space Operations System

Parallel Layered Control Architecture



A standardized mission architecture with parallel layering of peer space and ground functions will include interfaces and control to facilitate "plug and play" selection and integration of old and new technology components from disparate sources into varied, affordable and exciting mission systems. The mission architecture provides the "rules" for the structure into which elements will be integrated as operational concepts and technical feasibility dictate. Each layer now includes both a ground and a space component to accomplish together a major function such as navigation or maneuver planning. Functions are implemented to allow ground validation within an operational environment, and for transition of control between ground and flight systems. The optical navigation technology developed over the past decade and employed heavily for Galileo as a ground-controlled function with space components provided the basis for the autonomous optical navigation of the New Millennium program and the DS-1 flight. This example can be employed for the application of science planning, instrument analysis, and automated monitoring expertise to globally remote operation on planetary spacecraft of the late 1990's leading to a period of exploration with operable robust spacecraft requiring minimum routine care from ground-based operations controllers. The smaller spacecraft of the next generation with fewer instruments will both enable more flights, and for some investigations require more than one spacecraft. The investment in multimission trans-global architectures will be repaid in multiple flights.

Before the end-to-end mission architectures can be put into operation extensions are already appearing. The use of information system concepts in the development of the trans-global architecture can be extended to the "server" concept for groups of spacecraft operating to a single set of objectives, reducing the need to replicate the full control and support environment on each spacecraft. Server spacecraft may provide command and control, data management, communications and navigation for a tightly coupled set of spacecraft as in interferometry, or for a more loosely coupled set of spacecraft providing time, space, and instrumentation separation in the observation of a target of interest. Again, the ground-validation of technologies and the application of mature information system concepts will speed the time and reduce the complexity of validating new systems for flight. The next century will see the flight of not just autonomous spacecraft, but of autonomous systems which report back to earth-based operations rather than being minutely controlled from the ground.

5. Concurrent Mission Engineering with Trans-Global Architectures

Using the definition of mission operations as the application of space and ground resources, including people, to meet mission science objectives gains perspective on the scope of the work involved. The mission concept development then expands the mission objectives into an operational concept of what space and ground functions are to be performed, where people and automation are to be applied, and how the components function together as a mission information system to produce scientific observations and products. This concurrent engineering of the mission and of its mission information system produce a viable product for the tightly constrained budgets and schedules of the new classes of missions. Experienced designers have known for decades that this trade is beneficial, but the threat of mission cancellation for violating "caps" on life cycle costs has made the need imperative. Use of project design centers is a start in this process. The tools and capabilities available in the design centers must be expanded to improve the results.

During the concept development, planning tools represent the mission design and the mission components. Trades are made among the design options and mission components based on cost, availability, performance and schedule to produce a viable mission concept. Using a "click-and-play" system with model-based representations of existing and proposed components can greatly enhance the fidelity of the exercise. The attributes associated with each model include performance, cost, and environment to allow the visualization of the mission execution from the concept phase. The mission model then carries the expected operational behavior of the mission system forward during the "selling" phase of the mission and into the design and execution phases. Some research is expanding the option of using models as alternatives to detailed requirements for the test and validation of delivered products. The models may also be used as a management tool for performing end-to-end life cycle cost and performance trades during the execution of the mission, averting past experience of allowing underperformance in development of spacecraft and instruments as an underestimated impact on mission operations.

The use of a layered mission architecture with large stores of re-useable components allows a quick instantiation of the mission concept model in mission testbeds. Actual mission software can be configured quickly using an institutional knowledge base comprised of multimission components. The layered concept allows the development of needed layers for the initial testing of spacecraft breadboards and hardware in a rapid mission prototyping develment mode. New technology or components from diverse sources can be readily validated for their operational readiness. This provides an excellent path for the introduction and transfer of new technology. Once validated, the technology is immediately accessible to mission concept builders. Layers not required in early phases are "stubbed out" or represented by simulations. Using this approach, the full set of multimission operational analysis tools are available to support the development of spacecraft systems, and any added analysis or calibration tools developed for specific flight components are integrated into the developing operational systems in a continuing integration process rather than at a pre-launch massive exercise of integration and test.. The end-to-end system thus evolves from a simple, but mathematically proper subset of the full mission system into an incremental set of enhanced capabilites through a continuous testing and integration process until all operational functions are present and performing. An end-to-end mission testbed is provided as a distributed system with all re-useable system functions, models for known hardware components, and interfaces for breadboards, brassboards and actual hardware components to facilitate the rapid prototyping process. As the mission concept development reaches maturity in the development phase, separate copies are separated from the generic multimission testbed to become the neophyte new mission system. This process was first employed very successfully for the Mars Pathfinder mission and is now the model for how even faster, better, cheaper and even more innovative and exciting missions can be achieved.

6. Conclusions

The architectures, testbeds and new methodologies enable a new period of exciting space exploration by offering innovative missions at a fraction of the cost inherent in older technologies. The "plug and play" replacement enables the continued grown and insertion of new technology rather than the continued use of a limited and limiting set of options. The adoption of standard architectures for the trans-global end-to-end mission information system is essential to containing the cost and risk of space missions while inserting the new technologies which expand our explorations. Global partners should work together to share in the development of the trans-global architecture and to realize both the saving and the rewards of the new period of exploration.