Telescience in the Space Station Era
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ABSTRACT

After over a quarter of a century of experience in space, and the rapid evolution of Information System capabilities, there is a naturally growing demand for the development of systems where, to an increasing extent, participants can access their fellow scientists and the appropriate NASA services before flight, during flight and after flight, preferably from their home institutions and through the same equipment. This concept has become known as Telescience, and sporadic examples may be cited from earlier programs.

Our development of Telescience is a multidisciplinary effort involving scientists, engineers and technologists working together to integrate the emerging technologies and develop computer environments that maintain interoperability across different disciplines and different portions of the lifetimes of space experiments, conveniently called Teledesign, Teleoperations and Teleanalysis. Participants in the Telescience Testbed Program are using a rapid prototyping approach to evaluate the necessary technologies and select the options and trade-offs that best suit their accustomed modalities. It will be essential to include the international partners, since the development of uniform interfaces will be important to the program, and uniform access to databases from different instruments and spacecraft will increasingly be needed in attacking the vital global problems before us.

The concept of Transaction management will be described, where the emphasis is placed on the EFFECTS of commands, whether event-generated on board or sent up from the ground. If the instruments remain within their preassigned envelope of resources and privileges, no further checking is required. Some potentially hazardous operations will also require interlocks. This is conceptually simpler and safer than an elaborate model on the ground, with reliance on noise-free communications and a prohibition against reactive operations. In the majority of cases, it is expected that only fine adjustments will be made to optimize the data being gathered. Contingency planning will be needed for unpredictable events such as solar flares, supernovas, volcanic eruptions, etc., where rapid recognition and rapid changes in operations are needed to reap the maximum research benefit. The special needs of Security and Privacy will be briefly discussed.

Finally, we need to be concerned about the systematic ingest, cataloging and archiving of about three orders of magnitude more data than are presently being received, and the special requirements of video, or image data.

INTRODUCTION

The Space Station era will provide both unprecedented opportunities and unparalleled challenges to the conduct of science in space. After over a quarter of a century of space operations, flight instrumentation has grown in complexity as increasing demands are being made to improve on the available knowledge base. At the same time, computers have grown in capability and decreased in cost, so that every institution of Principal Investigator caliber has respectable computer facilities available, and scientists are beginning to use workstations at their desks that exceed the capabilities of the centralized mainframes of our student days. In addition, there has been tremendous progress in digital communications, and coast-to-coast links of high bandwidth are being constructed using both fiber optic lines and satellites. Packet switching is becoming available that allows bursts of bits to be sent at high speeds through common trunk lines without the need to pay the high costs of dedicated circuits which would be idle between data packets. Finally, the data rates expected are about three orders of magnitude more than we have been accustomed to handle in recent years. The Science and Applications user communities would, therefore, like to apply this emerging technology to conduct science in space, as far as feasible, from their home institutions, in a manner that approximates the use of a laboratory next door. These thoughts have led to the development of the TELESCEINCE concept.

Telescience implies the ability of a scientist to access remote services from his home institution, and to engage in computer conferencing with his colleagues for planning, scheduling, operations and correlative analysis. This requires a high level of computer connectivity, and includes the ability to interchange software tools as well as data, and to use multi-media communications (including voice and video, or image data). For convenience, Telescience may be roughly divided into the pre-flight, flight and post-flight portions called Teledesign, Teleoperations and Teleanalysis.

Teledesign includes the ability to send drawings, documents and specifications, to perform interactive design with remote facilities, and to conduct interface and other tests of instruments by remote computer access, as well as to perform the activities needed for operations planning and scheduling. The National Science Foundation now accepts proposals electronically, and for many years banking transactions have been carried out in this manner.

Teleoperations connotes the ability to conduct remote operations (in space) by making rapid adjustments to instrumental parameters and experiment procedures in order to op-

timize performance and obtain the best possible data. For some experiments, especially in the Life and Material sciences, this will also require direct communication with the Space Station crew using voice and video as well as digital instrument read-outs.

Teleanalysis involves the ability to access and merge data from distant sources, and to perform analyses and studies on computers that may be located at other institutions. This activity will generally commence during the flight phase, but usually extends far beyond the time of the actual flight. It includes the preparation of multi-authored manuscripts by electronic transfer, a practice that has made possible the iteration of a manuscript in at least one instance as much as 100 times in one month.

Figure 1 shows a highly idealized model, as it should appear to a user. User-to-user communications, user to databases and supercomputers, and user to operational spacecraft. Figure 2 shows in more detail the underlying architecture of the system needed to achieve this. The analogy may be made with a telephone system, where the users appear to have connections as shown in Figure 1, compared with the complexity of the underlying switching and transmission system similar to Figure 2, but completely transparent to the users.

TRANSACTION MANAGEMENT

The growing complexity of space instrumentation, and the desirability of making some processes reactive, or responsive to feedback from the space environment itself, have made it impossible to check "commands" by analyzing the bit stream on the uplink. Command checking would, in any case, need to be backed up by on-board safeguards, since errors can arise not only from noise in the radio frequency link, but also from failures or cosmic-ray induced corruption in the intervening electronic system, which is also growing in complexity. A great conceptual simplification results from considering not the signals that are sent into the instruments, but their potential effects. If these potential effects are within the permitted pre-allocated envelope of operations, the commands are executed. If not, they are denied, and a message is sent to the operators and the initiator to determine whether extra resources may be made available, whether denial is appropriate, or whether fault diagnostics should be initiated. It is especially important to note that this procedure of checking to ensure that each instrument operates only within its assigned envelope is invoked whether the "command" is initiated directly from the ground, or generated on board by a stimulus originating elsewhere on the payload. On the manned base, especially, there will also be two kinds of interlock. The first, an enabling interlock, will require positive action to make execution possible. This would be necessary for potentially harmful effects such as the firing of a squib or the ejection of material. The second, the disabling interlock, would be for a normally permitted operation which may be disabled if required; for example, the motion of a telescope within a

defined arc is normally permitted, but would be disabled if an astronaut is about to go out on EVA. Each user can be allocated an "operating envelope" which defines the allowable consumption of system resources such as power, cooling, crew time and telemetry, as well as the environmental rights and privileges for vibration, outgassing, etc. These envelopes will normally be scheduled in advance, vary from time to time, and will make it unnecessary to require users to submit their proposed uplink to labor-intensive bit-checking and payload modelling prior to transmission. An onboard "Operations Management System" (OMS) is currently being defined to perform the supervisory function needed to keep operations within the allocated envelopes, and to take the necessary steps to assure compliance or obtain an exception. Such a system will contribute directly to the safety of both the station and the equipment if the envelopes are set appropriately, and is an essential element in enabling the Telescience concept. It will also greatly simplify ground operations, since it will make it unnecessary for the Space Station operators to understand the details of instrument construction to the level that was needed when commands were checked on the ground prior to transmission to a spacecraft.

It is expected that, in the majority of cases, especially in the physical sciences, users will desire to make only minor adjustments to complex instruments, with negligible effects on system resources, environmental rights and privileges, but greatly improved data quality. A number of experiments in the Life and Material sciences will, however, be greatly enhanced by multi-media interactions involving the Principal Investigator (PI) team on the ground, and the crew in space. For events which cannot be predicted in advance, such as solar flares, supernova explosions, volcanic eruptions, etc., prompt recognition is essential, and major operational changes may be required rapidly, based on contingency plans developed in advance. Although such events are expected to be rare, they can be of great interest and importance. Special priorities need to be set for experiments that would be harmed by premature termination, such as sample crystallization; but the longevity of the Space Station makes it feasible, in most cases, to divert resources from one set of instruments to another, and to provide "make-up time" at a later date. It is essential for Telescience that adequate samples of (quick-look) data are available with minimum delay (latency), so that users can interact appropriately to modify their instrument adjustments and experiment procedures. It is important, also, to note that Telescience represents an enabling capability, and there is nothing to prevent a PI, if he wishes, to submit his operating plan well in advance, and await the eventual arrival of his data.

INTEROPERABILITY

The Space Station will be operated in conjunction with NASA's International partners in Europe (ESA), Canada, and Japan. Since NASA has prime responsibility for the safety of the station, a certain amount of interoperability must be built in for the manage-

ment of the operations. In recognition of the importance of team and campaign operations, where the major value is the correlative data that results from close coordination of the instrument operations, interoperability is also required for the information management and data acquisition systems. These will most logically be operated on a discipline basis, with distributed users but centralized management.

Utilization interoperability is required so as to place the instrumentation in that part of the Space Station best suited for it, and not necessarily in the facility supplied by the Principal Investigator's sponsoring institution. This implies the availability of standard racks with standard power, OMS, and telemetry interfaces. The team operations envisaged for experiments in the solar-terrestrial and earth science areas will require close collaboration by the participants, acting as a team, and joining in both the data acquisition and data analysis phases. The facility class instruments will need to be understood by all prospective users, and joint allocation schedules worked out by mutual agreement. It is likely that, in the U.S., the operations will be conducted through "Discipline Operations Centers" and in other countries through "Regional Operations Centers". To make best use of the large amounts of data expected, intelligent automated ingest schemes need to be developed that can perform at least the initial stages of cataloging, and to assist in the totality of the data management function, from acquisition through processing to archiving in retrievable and comprehensible form. Standard data formats are expected to be formulated on a discipline basis, and communication standards set that evolve towards the emerging International Standards Organisation-Open Systems Interconnection; the ISO-OSI standards.

Systems interoperability will be needed so that the Technical and Management Information System, TMIS, the Software Support Environment, SS+ERInd the Space Station Information System, SSIS, can be accessed from the same terminal using the same basic protocols and access techniques. TMIS is expected to be important in the pre-flight Teledesign phase, and will contain the documentation, schematics, manifests and planning schedules. Interoperability could be vital when schematics and instrument design details are needed on the Station from TMIS for servicing a malfunctioning payload operated through the SSIS. SSE will contain the rules and tools for writing software, primarily using ADA as the high level language of choice. Although ADA is not mandated for the PI instruments, it is expected that, if the SSE tools are as useful as anticipated, some PIs will elect to take advantage of them. Already one major University has designed a spacecraft control system in ADA, and their experience has made them supporters of that language. SSIS will be primarily used during flight, when Teleoperations will require support. Post-flight, the development of a Science and Applications Information System, SAIS, has been proposed as a concept whose time has come, with an architecture that can interface smoothly with the SSIS and to provide the

ability to merge data from different sources and different disciplines for correlative analyses and cause-and-effect studies. The implications of this desired interoperability are profound, but the aim is to guide the inevitable evolution of the computer environments of scientists into a converging direction rather than to let it proceed at random. This is consistent with major trends to avoid vendor proprietary systems and to proceed towards the implementation of the emerging OSI-ISO standards, some of which are still in the early stages of definition, but have the goal of enabling computers of all makes and models to intercommunicate through a carefully defined set of interface standards. These standards will enable users to interchange data, graphics, and the software tools needed to manipulate them, irrespective of the manufacturers of their computer systems.

SECURITY AND PRIVACY

The safety of spacecraft, especially of the manned variety, is of paramount concern to NASA. It follows that tight security will be needed to access the core system services, and privacy is a clear requirement for some communications with the crew. Such secure access may well need encryption, but this is not necessarily carried over into the user domain.

The competition for a small number of precious flight opportunities has become so fierce that flight instruments have grown in complexity to the extent that, in general, individuals outside the initial PI team would not be able to make much use of the telemetry if it is intercepted. Encryption, with its associated overhead, is therefore not desired by the majority of science users. The situation is different for commercial payloads; but there, the most secure and least burdensome technique is to encrypt at source and decrypt at destination. A variety of software and hardware techniques are currently available to accomplish this. The small minority of science users who wish to encrypt their data have the same solution available, without burdening the system with unneeded bulk encryption/decryption. Transaction management will also serve to ensure the safe management of payload operations without Space Station personnel being required to have a detailed understanding of the instruments and their data interpretation.

Access authentication for user payload systems is clearly of importance. It is expected that the identity of a user will need to be verified to a high degree of certainty, and his access limited to strictly specified portions of the payload by an access table that can be a function of time. This function may be performed in a manner analogous to that implemented in multi-user computer systems, where each user can operate independently of the others, and system level access is strictly limited to the operational personnel. The authentication procedure should not, however, be more onerous than necessary. Many techniques are now available, including passwords, call-back modems, thumb-print readers and magnetically coded cards. It is our contention that the safety of the spacecraft may be assured through the

security required for the core system, and the integrity of the payloads through the Transaction Management system, which can detect and prevent any excursions outside the pre-assigned envelopes. The users, who have worked hard for many years to obtain a flight opportunity, will usually be all too anxious to interrogate their payloads as often as possible. Thus, unauthorized and unwanted deviations from the expected operations should be quickly detected, and the appropriate action taken, whether the deviation is due to an instrument malfunction or a "hacker" intrusion. The burden of detecting payload malfunctions or unwanted intrusions into the payload should, therefore, be placed squarely where it belongs - on the users, and the Telescience approach makes this easier to achieve without undue time lags by the low latency required for Telescience versus the traditional time consumed in the production and shipping of tapes.

THE TELESCEIENCE TESTBED PILOT PROGRAM

The Task Force on the Scientific Use of Space Station and several ad-hoc working groups have made two important recommendations. The first is for the development of an interactive Telescience capability, and the second concerns the direct involvement of potential users in the design and development of the needed Information Systems and the implementation of a "rapid prototyping" methodology instead of the traditional "linear" process of providing requirements to the designers. The traditional approach has been for a representative group of users to provide "requirements" prior to system design and development, and then for the engineers to develop the information system based on their ability to understand the documented requirements without further interaction with the users. This has often resulted in a poor match between user desires and the final implementation, especially when the inevitable trade-offs have to be made between cost and performance. Such a methodology also makes it difficult to provide for evolving requirements and evolving technology.

The Telescience Testbed Pilot Project, TTPP, was, therefore, initiated in response to those recommendations. Sponsored by NASA's Office of Space Science and Application, OSSA, 14 groups from major Universities are supported by the University Space Research Association, USRA, under contract to NASA. This support represents incremental funding for PI-Class Institutions already supported by the discipline divisions of OSSA, and enables them to work together on testing, validating and refining the emerging technologies that apply to the performance of their scientific research. Together, they form a representative cross-section of the OSSA disciplines, and have held several workshops in conjunction with the Office of Space Station, the Office of Space Operations, the Office of Aeronautics and Space Technology, and the NASA Field Centers.

A few interim results may be cited from the initial operations of the TTPP which only started in the middle of 1987 is not due to submit a final report until December 1988. Together with the SAIS Working Group, the concept of Transaction Management with interlocks has been developed, as previously discussed. A generic user support environment has been defined, designed around intercommunicating workstations with generic software of general applicability, and an interface specification developed to support access and interaction with all the needed system resources. A Spacecraft control system written in ADA is being tested for its applicability to projects in other disciplines, and porting to other systems. Remote "browse" systems have been developed for limited bandwidth links. The use of forward error correction techniques for the remote control of instrumentation is being evaluated and appears to be promising in increasing the acceptable signal delay (latency). The use of limited video feedback for remote fluid handling in the Microgravity and Life Sciences area is being tested, as are video compression techniques for the remote performance of Spacelab type interactive Life Sciences experiments. Limited experience is being obtained with the direct merging of data from different spacecraft (including the provision of control capability to a partner institution) and field experiment campaigns. The TTPP is also evaluating the technology drivers for the accomplishment of Telescience, and developing a "key-passing" concept for the team operation of instruments in space without conflicts. Above all, valuable experience is being obtained by "proto-PIs" in Telescience concepts, and they have concluded that Telescience is clearly their methodology of choice.

Figure 1

Figure 2