Distributed Interactive Simulation for Space Projects

L. Argüello & J. Miró
Modelling and Simulation Section, ESA Directorate of Technical and Operational Support, ESTEC, Noordwijk, The Netherlands

Distributed Interactive Simulation is an innovative technology that will dramatically change the way in which simulation is developed and applied in space projects. It will only be effective, however, if based on well-accepted standards, such as the IEEE High-Level Architecture (HLA) standard. A number of studies and experiments have been carried out as part of ESA's R&D effort to evaluate the benefits of distributed simulation for space projects in general, and the International Space Station in particular. These have led to the first ever applications of the HLA standard to the space domain. Promising results have already been obtained with the simulation of the Automated Transfer Vehicle's rendezvous with the Space Station and of satellite payload operations, which can be extrapolated to other space projects and scenarios.

What is distributed simulation and what are its benefits?

Distributed Interactive Simulation (DIS) allows geographically separated simulators to work together, interacting in real-time, to provide predictions just like a single integrated simulator. The technology also allows real entities to be included in the simulation loop. Before this approach can be applied to space projects, however, it has to be established whether current simulation and communications technology can effectively support the critical requirements of space scenarios. It also needs to be demonstrated that this approach results in a cost-effective solution compared with the conventional approach of centralised simulators.

These questions have been addressed in a number of studies at ESA, including early experiments conducted in the framework of a co-operation between ESTEC and the Gagarin Cosmonaut Training Centre (GCTC) in Russia. The distributed interactive simulation paradigm can be implemented in many ways, but in order to become a useful technology it has to be based on a standard defining the interface between two interacting simulators/entities, i.e. defining how two or more simulators/entities have to talk to each other. The co-operation between ESTEC and GCTC has led to the first ever application of this technology in a space context, based on well-accepted standards.

The technical challenge

The technical issues involved in implementing the distributed-simulation paradigm are related to interoperability and to the communications links. Interoperability requires the simulator to respect a certain architecture in order to be able to communicate with the outside world. As far as the communications links are concerned, the main difficulty is in coping with the time-span data requires to travel from the originating simulator to the receiving one (the so-called 'latency'). In a real-time simulation, the distribution of the simulation models at remote sites introduces an error, because the data required by one model from another physically remote model needs a finite time to travel over the network. Assumptions about the current values of the remote model parameters therefore need to be made on the basis of earlier values (extrapolation using 'dead-reckoning algorithms').

The key question to be answered here is whether the error introduced by the distribution of the simulation can be kept within pre-defined, acceptable error bounds. This is evaluated by comparing results obtained from the distributed system with those obtained from the non-distributed system. This will be particularly critical for simulation applications involving closed control loops, such as are encountered in attitude and orbit control systems. For simulations with flight software and hardware in the loop also, the response time expected from the simulator will constitute a critical challenge for this approach. In addition to the latency, the real-time behaviour of the communication link will also be a critical requirement for real-time simulations, and one not always possible to meet with conventional communication protocols.

The network requirement is also an important issue. Setting up a complex communications scheme is often difficult and requires considerable effort. The application of modern DIS technology not only simplifies the distribution of the data and the supporting network architecture and protocols required, but also reduces the bandwidth needed to a minimum, making the use of affordable ISDN lines and equipment possible.

Applicable standards

The first standard for interactive distributed simulation was IEEE 1278.1, also known as the DIS protocol. This standard, whose generation was sponsored by the US Department of Defence through the Defence Modelling and Simulation Office (DMSO), was applied extensively in defence simulations. It was based on the use of standard formatted packets, designed for the data required by these specific applications. Problems due to the inflexibility and lack of scalability of this approach have eventually led to a completely different approach, the High Level Architecture (HLA), which is in the process of becoming the IEEE 1516 Standard.

The elements of an HLA-compliant distributed simulation are summarised in Figure 1. The various components of the 'federation', the 'federates', are described using the Object Model Template (OMT). During a distributed simulation, the federates must interact in accordance with the HLA interface specification. While HLA is an architecture, the Run Time Infrastructure (RTI) is the software needed to support simulation execution.

Practical experience

To evaluate the distributed simulation approach for space, a number of practical applications (experiments) have been implemented. The first ever application of this technology to the space domain was demonstrated in the framework of the co-operation between ESTEC and GCTC. The results obtained both confirmed the feasibility of the approach and highlighted the critical issues for its application in the space domain. The resulting demonstration system was deployed to European industry, and facilitated the initiation of several related R&D activities in the frame of the European Union programme for High Performance Computer Networks (HPCN).

Another experiment was performed in parallel using a satellite simulator to validate the use of HLA in the context of distributed payload user centres. The application of distributed simulation in the context of the International Space Station, and more precisely for spacecraft proximity operations, was further investigated in the framework of ESA's Technology Research Programme (TRP).

The results of these activities are summarised in the following paragraphs.

Spacecraft rendezvous

A distributed simulation of the rendezvous and docking (RVD) of the Automated Transfer Vehicle (ATV) with the International Space Station (ISS) has been implemented in order to validate the technology in a challenging space scenario. This scenario is particularly critical due to the very tight coupling of the two spacecraft through the ATV trajectory control loop, and the very small tolerances for the docking in terms of linear and angular displacements. This means that the accuracy requirements for the position and velocity of the interacting spacecraft are very high, and the error introduced by the communication latency has to be kept at least one order of magnitude below the docking tolerances.

Several simulation experiments were carried out with simulation nodes at ESTEC, GCTC, ESOC and several industrial sites in Europe.

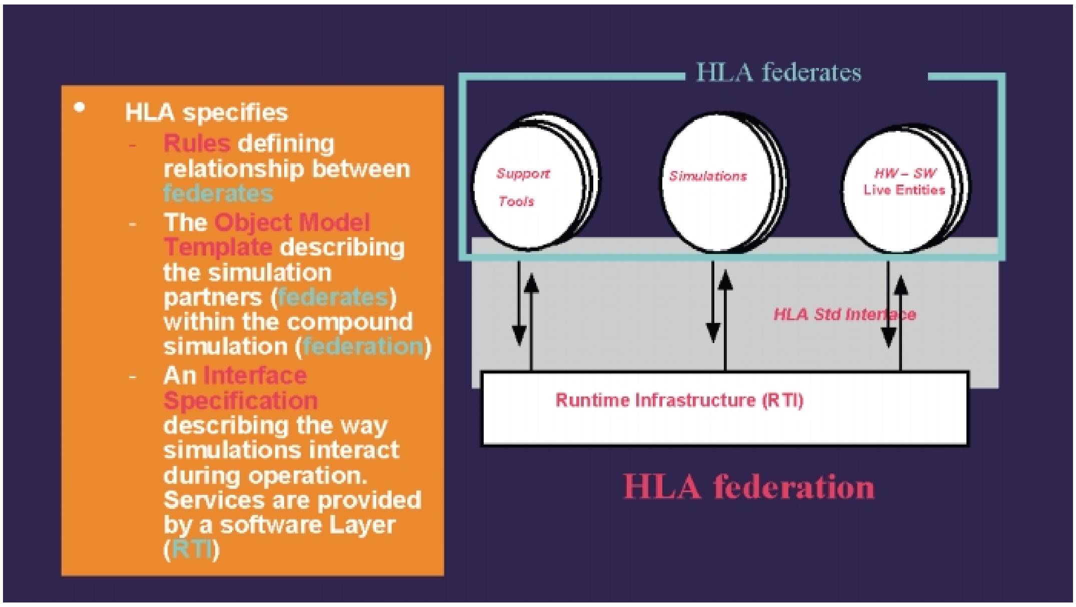
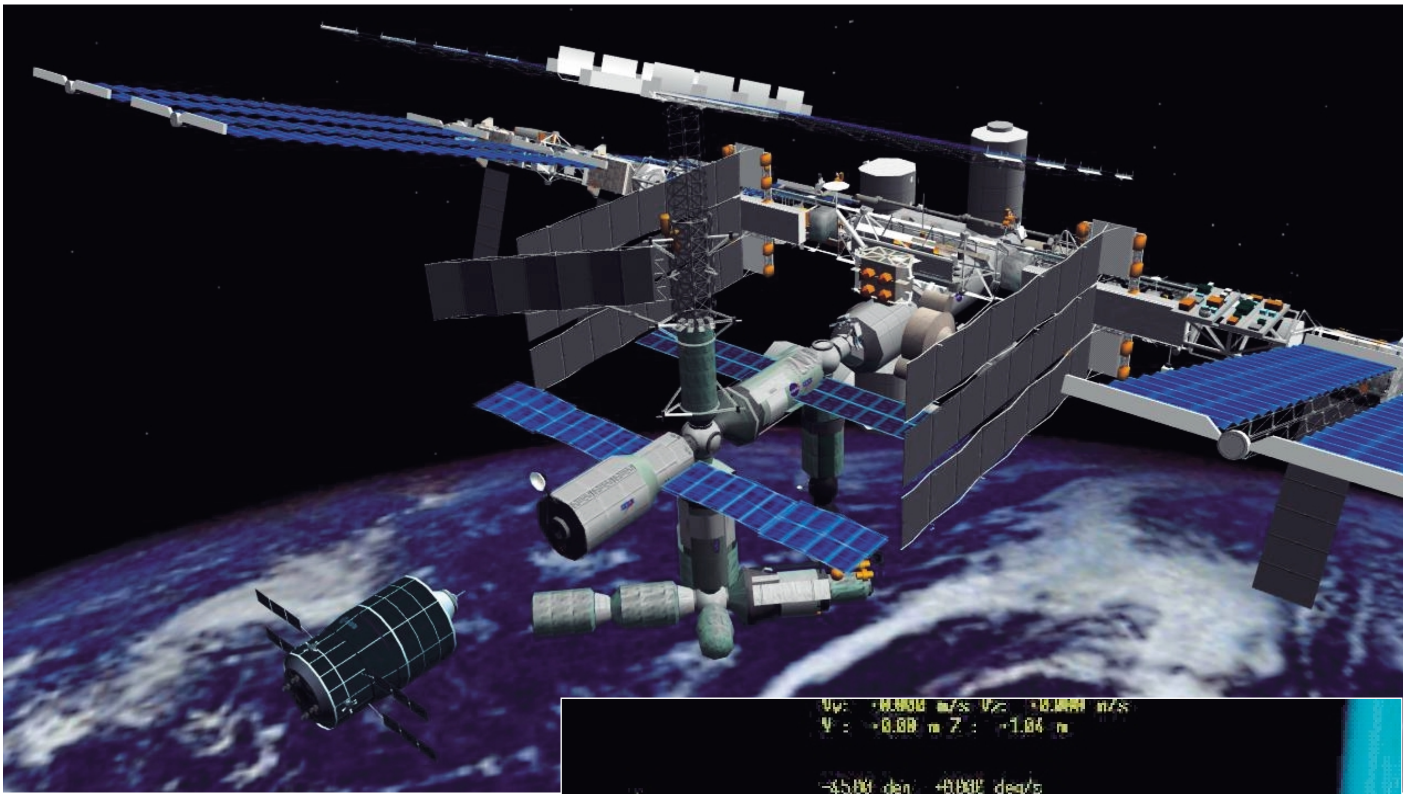


Figure 1. Overview of an HLA-compliant distributed simulation



The RTI software infrastructure required to implement an HLA federation was made available by the DMSO. The use of ISDN as the basic communications infrastructure was selected as the most cost-effective and practical solution.

Mission scenario

The simulation scenario was the rendezvous and docking of the ATV to the ISS both in automatic and in manual mode. 3D visualisation was used to monitor the manoeuvres and to assist the manual control, activated in case of contingencies. Figure 2 shows the final approach manoeuvre from above. Figure 3 shows a view through an ISS-mounted camera, used to monitor the final metres of the approach. The overlay parameters provide information on relative position and attitude.

For the purposes of DIS, it was decided to concentrate only on the ATV manoeuvres to be performed near the Station, the beginning of the final translation being selected as the starting point for the simulation scenario.

Context

Three different demonstration scenarios relating to the Rendezvous and Docking (RVD) of the ATV to the ISS were selected, pertinent to different phases in the ATV development life-cycle:

– The collaborative engineering context assumes distributed simulation involving geographically distributed industrial partners responsible for different parts of the ATV. The emphasis here is on the early detection of problems, which can occur long before system integration is attempted. This should also help shorten the development cycle.

– The operational procedure validation context assumes the need to define the procedures and the parameters to be monitored and associated thresholds for nominal and contingency scenarios, involving more than one ISS segment.

– The mission rehearsal and training context assumes the need for multi-segment integrated simulations involving several control centres and the crew. It also covers remote access to high-fidelity simulations for crew members.

Figure 2. Three-dimensional visualisation of the ATV approaching ISS

Figure 3. The ATV viewed through the ISS camera

Distributed scenario
The entities represented in the simulation ('federation' in HLA terms) are the ATV vehicle (federate called ATV-F), the ISS (ISS-F) and the Mission Control Centre (MCC-F). A federation manager (FM-F) was defined to implement the simulation control functions. Switch over from automatic to ISS crew control is decided by the MCC, which also prescribes the flight plan and monitors the manoeuvre.

Table 1. Functions allocated to the different ATV/ISS RVD simulation modes

ATV-F:
- GNC subsystem
- Chaser orbital mechanics (differential equations of motion)
- Computation of Chaser dead-reckoning (DR) parameters
- Reconstruction of the Target (ISS) variables using its DR parameters
- Computation of variables describing relative (ATV-ISS) motion
- Computation of parameters and variables for the GUI
- Process inputs from the remote control post
- Introduction of failures and contingencies onboard ATV

ISS-F:
- Target GNC subsystem
- Target orbital mechanics (differential equations of motion)
- Computation of Target dead-reckoning (DR) parameters
- Reconstruction of the Chaser variables using its DR parameters
- Computation of variables describing relative (ATV-ISS) motion
- Computation of parameters and variables for the GUI
- Remote control post functionality
- Computation of the position of Sun
- Module to initiate CAM

MCC-F:
- Reconstruction of Chaser and Target variables using DR parameters
- Remote control post functionality
- Computation of variables describing relative Chaser and Target motion in various coordinate systems (for 3D and 2D graphics, data logger)
- Algorithms to form and modify the Mission Plan for Chaser

FM-F:
- Federation management (commands like "restart", "resume", "pause")
- Changing of the time-scale factor
- Introduction of failures and contingencies

The geographical allocation of the above federates is configurable, but for the experiment the configuration selected (Fig. 4) was: ISS simulated at GCTC (Star City, Russia), ATV simulated at ESTEC (Noordwijk, The Netherlands), and the Mission Control Centre federate simulated at ESOC (Darmstadt, Germany). Table 1 shows the functions allocated to the different simulation nodes.

Results
The limits considered allowable based on the simulation requirements were expressed in the form of misalignments of 0.02 m in position and of 0.3 – 0.5 deg in orientation. However, this is not sufficient in order to assess some of the integral performances of a simulation session, e.g. it is conceivable that the differences in state vector components are within the prescribed boundaries, but that the total amount of fuel consumed differs considerably compared to the non-distributed simulation. This would render the simulation inadequate, since it could trigger wrong decisions and unnecessary changes in control strategy.

The simulation results show that the accuracy criteria are met even for an acceleration of the simulation by a factor of 4 with respect to real time. This is equivalent to increasing the latency by the same factor. It was therefore proven that the delay introduced by the distributed approach does not affect the overall validity of the simulation.

Distributed payload user centres
A distributed simulation experiment has been carried out at ESTEC taking a small technology-demonstration satellite mission, Proba, as a basis. The purpose of this experiment was to evaluate the applicability of HLA for familiarising and training satellite payload users.

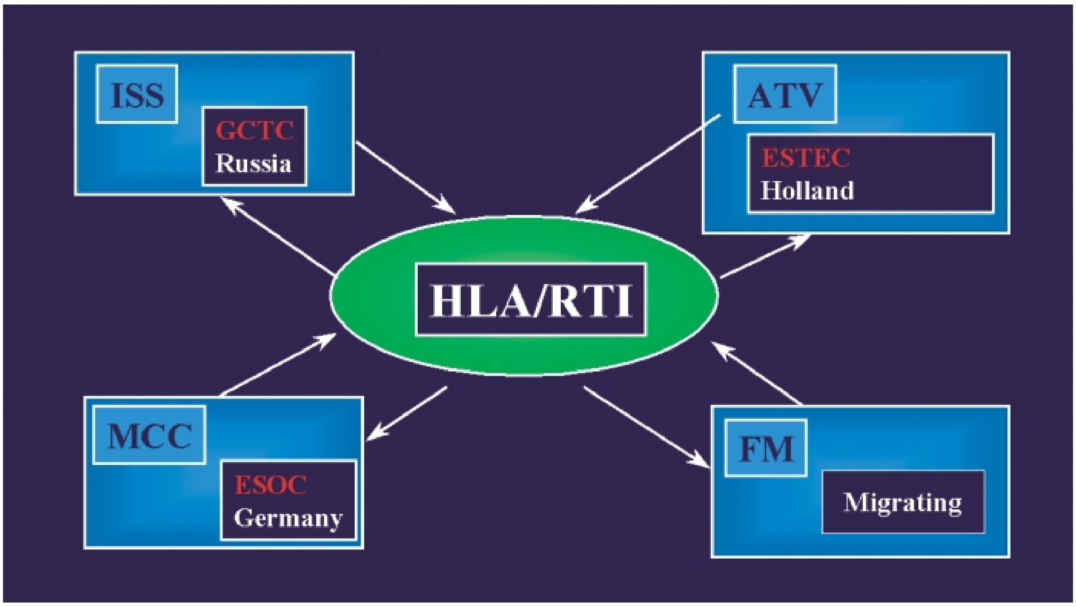


Figure 4. Geographical configuration of the RVD distributed simulation

Mission scenario
The Proba simulation focussed on one of the payloads, namely an imager. Its users, distributed at different locations, will be able to send observation requests to the satellite (via the Control Centre) and will receive directly the image requested. The mission-simulation part of the Project Test Bed has been re-engineered to work in a distributed configuration. Using the distributed approach allows the parallel transmission of various selections of the telemetry produced by the simulator to several remote monitors in parallel, and the reception of telecommands from a remote user station.

The distributed simulation experiment (Fig. 5) consisted of the mission simulator and the separate control and monitoring tasks (telecommand, telemetry, event table MMIs, Earth track graphical displays and 3D visualisation) running in a distributed manner, both at ESTEC in Noordwijk, representing the mission Control Centre, and at Headway (UK) simulating the remote user centre.

The users located at the remote user centres are able to:
– send observation requests to the Control Centre
– monitor the outcome of spacecraft autonomous operations following user image requests
– display spacecraft position, orbital track and ground-station visibility zones on a 2D map.

The Control Centre at ESTEC is able, in addition to the user operations, to:
– uplink telecommands and downlink housekeeping data when the spacecraft is in contact with the ground station
– monitor an on-board event table containing the housekeeping history from the last ground-station contact
– provide visualisation of a realistic model of the spacecraft overlaid with spacecraft body vectors as well as Sun-, Moon- and Earth-pointing vectors, and real-time visualisation of the pointing manoeuvres required during the mission lifetime (i.e. Earth, ground-station and user-station pointing) on the 3D visualisation (Fig. 6).

In particular, the test executed demonstrated the stability of the distributed system while the distributed federates join and leave the federation. Data updates were not affected by federation management.

Lessons learnt
The advantages of distributed simulation versus the conventional approach are: earlier availability of the simulation (since it can use pre-release versions), savings in the time and effort needed for installation of simulation products locally, savings in computer hardware, and access to simulations not otherwise available (e.g. access to high-fidelity simulations at industrial sites).

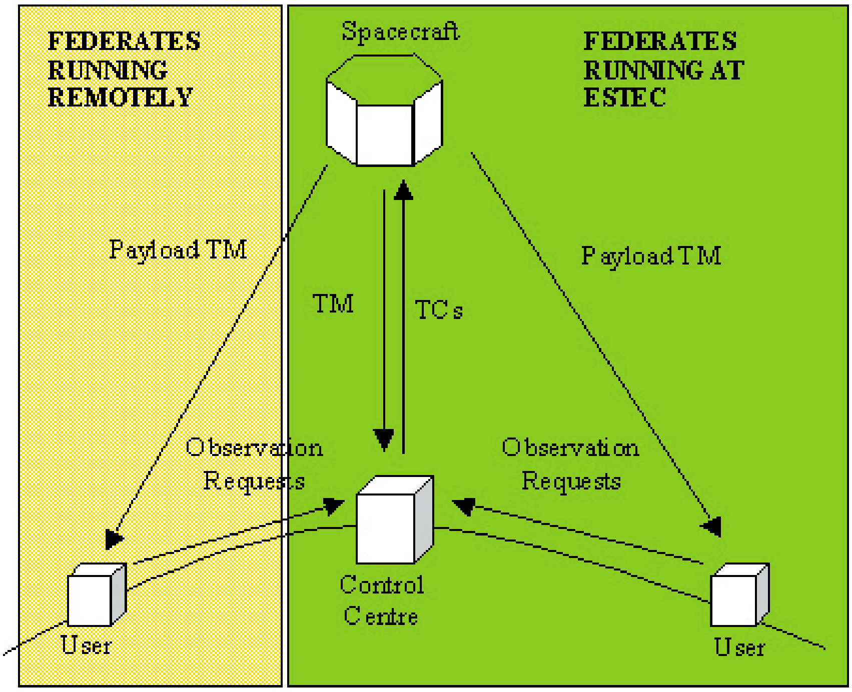


Figure 5. Overview of the Proba project test-bed distributed simulation

In particular, in the case of the ATV study, productivity gains and a reduction of 20% in development time seem achievable through collaborative engineering during the development phase, depending on the duration and scope of the simulation campaign. Early analysis of coupled effects is an area where distributed simulation becomes an enabling technology.

In the case of the ISS, for example, the potential of distributed simulation to save development effort and time is significant due to the distributed nature of the project, involving numerous geographically separated partners, and to the large number of simulation facilities distributed throughout the world. The use of distributed simulation in support to the multi-segment operations and training involving crew and ground-station personnel within the International Space Station programme is in the process of evaluation.

The HLA standards are in the process of becoming an IEEE standard and show considerable potential for being widely applied in a variety of simulation domains. The real-life experiments carried out by ESA and summarised here highlight the potential to support operations preparation tasks using affordable, commercial ISDN lines. Since the use of this technology only makes sense in a global context, its broad adoption by industry

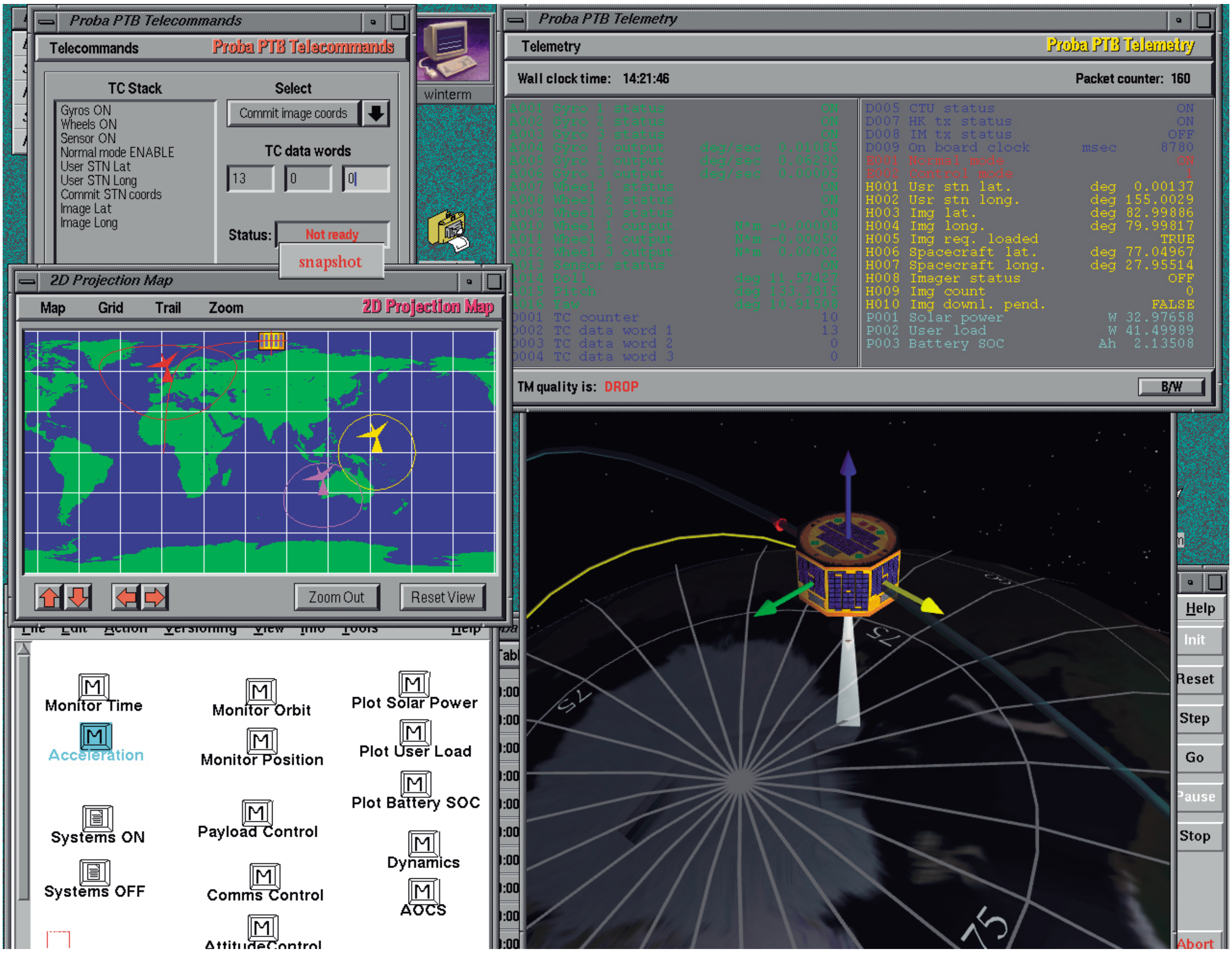


Figure 6. A typical Proba test-bed simulation

and other space agencies is required before it can be exploited effectively.

Some critical issues associated with this technology also need to be pointed out. The tools needed to build the distributed simulation system according to the HLA standards are only starting now to become available. The software infrastructure needed to conduct distributed simulations has not yet reached the standard of a commercial product. Distributed interactive simulation also conflicts with the implementation of computer-access security measures in that dedicated systems have to be placed outside firewalls or access through firewalls needs to be granted. Last but not least, significant expertise is required to configure the simulation computers to communicate over ISDN lines.

Future work

It is planned to focus the future work on three specific areas:

– Deploying the distributed rendezvous simulation system implemented in the ESA R&D effort for a transatlantic demonstration involving NASA and ESA: this would allow NASA to evaluate this technology for ISS operations and training.
– Establishing a prototype infrastructure at European level to facilitate the use of this technology by space industry in support of collaborative engineering: the infrastructure should include a space federation model, guidelines for plug-and-play in this federation, and the associated software tools.
– Extending the demonstration to simulation systems including flight hardware in the loop, typically the on-board computer.

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