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# SOLAR AND HELIOSPHERIC OBSERVATORY (SOHO) EXPERIMENTERS' OPERATIONS FACILITY (EOF)

*Eliane Larduinat, AlliedSignal Technical Services Corporation*
*William Potter, Goddard Space Flight Center, Code 514*

## ABSTACT
This paper describes the SOHO Instrumenters' Operations Facility (EOF) project. The EOF is the element of the SOHO ground system at the Goddard Space Flight Center that provides the interface between the SOHO scientists and the other ground system elements. This paper first describes the development context of the SOHO EOF. It provides an overview of the SOHO mission within the International Solar-Terrestrial Physics (ISTP) project, and discusses the SOHO scientific objectives. The second part of this paper presents the implementation of the SOHO EOF, its innovative features, its possible applications to other missions, and its potential for use as part of a fully integrated ground control system.

Keywords:
Solar and Heliospheric Observatory (SOHO), Instrumenters' Operations Facility (EOF), EOF Core System (ECS).

## INTRODUCTION
The SOHO mission is part of the ISTP program. The SOHO EOF is the focal point for instrument operations, experiment planning and science data analysis. The EOF will support the instrumenters in three main functional areas: (1) commanding and monitoring of the instruments' health and safety, (2) receiving and archiving telemetry data, and (3) planning and scheduling of coordinated scientific observations. The particularities of the SOHO mission have dictated and influenced the design of the ECS.

This paper presents the software design for the ECS as well as the physical architecture of the EOF. It also discusses the various choices made, cost savings and risk mitigation realized and the possibilities of reuse of the SOHO EOF for other missions.

## SOHO MISSION OVERVIEW
The ISTP program is an international space exploration program involving spacecraft built and managed by the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and the Institute of Space and Astronautical Science (ISAS). This space program is coordinated with ground-based and theory investigations. Its intent is to coordinate worldwide studies of Sun-Earth plasma interaction, solar and heliospheric physics and global geospace physics. The ISTP program involves several spacecraft: SOHO, the Plasma Turbulence Laboratory (CLUSTER), the Geomagnetic Tail (GEOTAIL), the WIND spacecraft and the POLAR spacecraft.

SOHO is a joint venture between ESA and NASA: ESA provides the spacecraft that is built and tested in Europe and NASA provides the launch vehicle, launch services and the ground segment to support all pre-launch activities and in-flight operations. SOHO is scheduled to be launched in July 1995 and will be injected in a halo orbit around the L1 Sun-Earth Lagrangian point, about 1.5 million kilometers sunward from the Earth. The SOHO spacecraft will be three-axis stabilized and pointing to the Sun. The total mass will be about 1350 kg and 750 Watts power will be provided by the solar panels. The payload will weigh about 650 kg and consume 350 Watts in orbit.

The SOHO mission duration is 2 years and 5 months and will consist of three main phases:
(1) Launch and early orbit phase which starts at liftoff and includes the coasting period in parking orbit.
(2) Transfer trajectory phase during which the spacecraft will travel from Earth orbit to the halo orbit (Some science observations may begin during this phase).
(3) Halo orbit phase which starts with the commissioning of the service module and the on-board instruments (approximately one month), after which the nominal routine operations will start for a duration of at least 2 years.
SOHO is equipped with sufficient on board

consumables for an extra four years in orbit. SOHO will carry eleven on-board instruments.

## SOHO Scientific objectives

The SOHO scientific objectives are to study (1) the structure (density, temperature and velocity fields) and dynamics of the outer solar atmosphere, (2) the solar wind and its relation to the solar atmosphere, and (3) the structure, chemical composition, and dynamics of the solar interior.

SOHO will carry a set of telescopes to study phenomena initiated below the photosphere, and propagating through the photosphere, chromosphere, and transition region into the corona. They will investigate problems such as how the corona is heated and transformed into the solar wind that blows past the Earth.

Spectrometers will study the emission and absorption lines produced by the ions present in the different regions of the solar atmosphere, allowing to determine densities, temperatures and velocities in the changing structures. These measurements will be complemented by the "in situ" study of the composition and energies of the solar wind: particle detectors will sample the solar wind as SOHO passes through it.

While the solar interior is the region that generates the kinetic and magnetic energy driving outer atmospheric processes, almost no direct information can be obtained about any region below the photosphere. The neutrinos generated by the nuclear reactions taking place in the core, are the only direct radiation that reaches us from below the photosphere. Helioseismology is a relatively new technique developed in the last two decades, allows us to study the stratification and the dynamic aspects of the solar interior. It analyses the acoustic and gravity waves that propagate through the interior of the Sun and can be observed as oscillatory motions of the photosphere. The analysis of these oscillations allow us to determine the characteristics of the resonant cavities in which they resonate, much in the same way as the Earth's seismic waves are used to determine the structure of the Earth interior. To study the solar interior, SOHO will carry a complement of instruments whose aim is to study the oscillations at the solar surface by measuring the velocity (via the Doppler effect) and intensity changes produced by pressure and gravity waves. This requires both high resolution imaging and long uninterrupted time series of observations. In addition, because it is of prime importance to understand the structure of the Sun in relation to the oscillation measurements, the total solar irradiance and its variations will be measured.

## SOHO Instrumentation

The SOHO instruments can be divided into three main research groups: helioseismology, solar atmospheric remote sensing, and "in situ" solar wind measurements. Table 1 provides a list of the eleven SOHO instruments, indicating the corresponding research group and the primary institution responsible for their development.

The helioseismology instruments, GOLF, MDI and VIRGO, primarily aim at the study of those parts of the solar oscillations spectrum that cannot be obtained from the ground because of noise effects introduced by the Earth's diurnal rotation as well as the transparency and seeing fluctuations of the Earth's atmosphere.

The solar atmospheric remote sensing instruments, CDS, EIT, LASCO, SUMER, SWAN and UVCS, constitute a set of telescopes and spectrometers studying the dynamic phenomena that take place in the solar atmosphere at and above the chromosphere. The plasma will be studied by spectroscopic measurements and high resolution images at different levels of the solar atmosphere.

The "in situ" investigation of the solar wind is carried out by CELIAS and CEPAC, that will determine the elemental and isotopic abundance, the ionic charge states and velocity distributions of ions originating in the solar atmosphere. The energy ranges covered will allow us to study ion fractionation and acceleration from the "slow" solar wind through solar flares.

SOHO will be placed in a halo orbit around the L1 libration point. The halo orbit will have a period of 180 days and has been chosen

**Table 1. SOHO Instruments**

| Instrument Name | | Primary Institution |
|---|---|---|
| **Helioseismology** | | |
| GOLF | Global Oscillations at Low Frequencies | Institut d' Astrophysique Spatiale, France |
| MDI | Michelson Doppler Imager | Stanford University, USA |
| VIRGO | Variability of Solar Irradiance and Gravity Oscillations | Physikalisch-Meterologisches Observatorium Daos, Switzerland |
| **Solar atmospheric remote sensing** | | |
| CDS | Coronal Diagnostic Spectrometer | Rutherford Appleton Laboratory, U.K. |
| EIT | Extreme-ultraviolet Imaging Telescope | Institut d'Astrophysique Spatiale, France |
| LASCO | Large Angle Spectrometric Coronagraph | Naval Research Laboratory, USA |
| SUMER | Solar Ultraviolet Measurements of Emitted Radiation | Max Planck Institute, Germany |
| SWAN | Solar Wind Anisotropies | Service d'Aeronomie du CNRS, France |
| UVCS | Ultraviolet Coronagraph Spectrometer | Smithsonian Astrophysical Observatory, USA |
| **"In situ" solar wind measurements** | | |
| CELIAS | Charge, Element and Isotope Analysis System | Max Planck Institute, Germany |
| CEPAC | COSTEP-ERNE Particle Analysis Collaboration | University of Turku, Finland |

because it provides a smooth Sun-spacecraft velocity change, which is appropriate for helioseismology, it is permanently outside of the magnetosphere, which is appropriate for the "in situ" sampling of the solar wind and particles, and it allows permanent observation of the Sun, which is appropriate for all the investigations.

During in-orbit operations, the Deep Space Network (DSN) will receive telemetry during three short (1.3 hours) and one long (8 hours) passes per day. Outside of passes, the science data will be recorded on-board and played back during the short passes. The MDI instrument generates a high rate data stream that will be transmitted only during the long station pass. For two consecutive months per year, DSN will support continuous data transmission, including MDI high rate data. Whenever there is data transmission, the basic science data (40 kbits per second) will be available in near real-time at the EOF.

**EOF within the SOHO Ground System.** The SOHO EOF is part of the NASA Goddard Space Flight Center ground system where it is co-located with the Payload Operations Control Center and the Command Management System. The functions within the EOF are focused on instrument operations. A separate analysis facility, dedicated to the scientific analysis of the SOHO data, will be located in a separate building at the Goddard Space Flight Center.

The EOF is comprised of two main elements:

- The ECS which provides the communications between the instrumenters and other elements of the SOHO ground system. The ECS includes hardware and software to support the primary functions of instrument commanding, telemetry reception, distribution and archiving, and science planning and scheduling. The ECS includes two specialized workstations: the science operations coordinator's workstation and the project scientist workstation.
- The Instrumenters WorkStations (IWS) which include hardware and software provided by the individual instrument teams dedicated to the operation of a given instrument and its science analysis for planning purpose.

The instrumenters may be "resident instrumenters" and be located at the EOF where they have data processing equipment, or

IWSs. The ECS supports near-real-time commanding capabilities and distribution of real-time telemetry for the resident instrumenters. The "remote instrumenters" are located outside of the EOF, that is at their home institution in the US or in Europe. Mainly for security reasons, they may only communicate with the EOF via file transfer. They do not have access to the near-real-time commanding and real-time telemetry distribution capabilities. They can perform preplanned commanding and they can access the telemetry data archived within the ECS. They may also use the telephone or facsimile to communicate with the flight operations team or with an EOF resident team member in order to request changes in their instrument status.

The major ground systems elements that interface with the SOHO EOF are:

- The Information Processing Division (IPD) Packet Processor (Pacor) which captures the telemetry data from DSN via NASCOM and transfers the real-time telemetry to the EOF.
- The IPD Data Distribution Facility (DDF) which provides quicklook telemetry files (mainly tape recorder dumps) to the EOF.
- The ISTP Central Data Handling Facility (CDHF) which provides orbit and attitude data to the EOF and receives other mission support data from the EOF.
- The Command Management System. which serves as the intermediary between the EOF and the Payload Operations Control Center for instrumenter commanding activities.

The ECS will communicate via the NASA Science Internet network using file transfers with international observatories and scientific institutions including, but not limited to, the instrumenters home institutions, ESA, the National Solar Observatory (NSO), the ISTP Science Planning and Operations Facility (SPOF), and the NASA Space Science Data Center (NSSDC).

## SOHO EOF DESIGN CONCEPTS

Several considerations and choices have highly influenced the EOF design.

- Conformity with the spacecraft integration and test environment.

In order to minimize development efforts on the part of the instrumenters, the ECS interface with the instrumenters was closely modeled after the interface provided by the spacecraft contractors during the integration and test phase. Some modifications have been necessary to go from a test to an operational environment, but the efforts to maintain that protocol as much as possible have greatly facilitated the integration of the various instrument teamswith the ECS.

- User involvement.

The EOF users were involved as much and as early as possible. Scientists and members of the flight operations team actively participated in the definition of the functional requirements. Additionally, an interface control document was developed very early in the project life cycle. This was of great benefit when dealing with instrument teams that had little contact with each other at the beginning of the project, and whose main concern at that time was not the details of the daily operations.

- Need for adaptability and flexibility.

The functional needs of the various instrument teams are very different. Some SOHO instruments, mainly the coronal imaging instruments, will be operated interactively every day in real-time. Some other instruments (CEPAC, CELIAS, VIRGO, GOLF) will generally operate automatically and will not need real-time operational control except for surveillance of housekeeping data. Consequently, some teams will need to command their instruments and receive the telemetry in real-time, while some other teams will command in the traditional preplanned manner from a remote site and only retrieve telemetry files on a daily or weekly basis.

The instrumenters' requirements on the ECS will also vary during the lifetime of the mission. All the eleven instrument teams will bring in their own equipment for integration into the EOF and most of the teams are planning to be at the EOF during the initial phase of the mission. After the spacecraft is commissioned, only 6 teams are expected to remain located in the EOF while the others teams will return to their home institutions.

The IWSs are supplied by the individual instrument teams and represent a wide range of hardware and software. The ECS must provide connectivity for each IWS and between IWSs. The ECS must be capable of establishing connections with the SOHO ground e4lements, the analysis facility and with the outside world. The ECS must satisfy stringent performance requirements. It must be able to sustain the real-time telemetry and commanding rates, it must have sufficient storage capacity to archive the science data. Finally, it must be able to support two month per year of continuous science operations.

• Software Reuse.

As much as possible, the ECS design incorporates standard off-the-shelf hardware and software. The main software systems that have been reused in the ECS design are:
(1) the Transportable Payload Operations Control Center (TPOCC), which has been used to support what is referred to as "Global Services" functions such as inter-tasks communications, event generation and event logging. TPOCC also provides an extensive library of routines that have been reused in the ECS implementation.
(2) the Interactive Experimenter Planning System, was used as the basis for the implementation of the ECS science planning and scheduling functions. These functions include batch and interactive scheduling, conflict resolution and automatic scheduling and re-scheduling of activities.

• Rapid prototyping development approach.

Several software prototypes have been developed during the ECS design phase to verify major design choices. In particular the following was evaluated or verified: hardware performance for telemetry distribution, applicability of reused software, and demonstration of operator's interface implementation to the users.

• Adoption of implementation standards.

Representatives of the ECS development team attended all the science operations working group meetings, presented various draft of the interface control document, and were able to help and participate in the choice of a set of standards such as : X-Windows (X 11), Motif, Interactive Data Language (IDL), TCP/IP Ethernet, Flexible Image Transport System formats, Standard Formatted Data Unit, Structured Query Language and Standard U.S. commercial power and receptacles

## SOHO EOF IMPLEMENTATION

### Facility

The EOF facility is located in Building 14 at the Goddard Space Flight Center. It consists of offices for the project scientist, the science operations coordinator and the various instruments teams. It also includes a large conference room and various equipment such as telephones, fax machine, color printer, scanner, etc. The ECS equipment is located in the science operations coordinator's office. The EOF is also located next to the mission operations center, where the flight operations team will control the day-to-day operations of the spacecraft

### Software

The ECS software is comprised of five major subsystems:

(1) The telemetry subsystem receives the real-time telemetry from Pacor and distributes it to the resident instrumenters according to their requests. It also receives files of quicklook telemetry, primarily containing tape recorder dumps from DDF. The telemetry subsystem archives all the SOHO telemetry data for a period of seven days. The archived telemetry is made available in the form of files to the SOHO scientific community.

(2) The commanding subsystem supports the real-time as well as the preplanned commanding functions. It receives the commanding data from all the instrumenters and it provides a single interface to the Command Management System and the Payload Operations Control Center.

(3) The planning and scheduling subsystem provides an automated tool to produce an integrated and conflict-free observation plan. It can merge the individual instrument plans, accept input from the science operations coordinator, incorporate predefined constraints such as DSN schedule and reserved times for spacecraft activities. This subsystem was based on reused software, but it was re-implemented using an object-oriented

methodology as described in more details below.

(4) The user interface subsystem provides a set of windows that will enable the science operations coordinator to monitor and control activities within the EOF.

(5) The "global services" subsystem supports functions such as inter-task communication and event logging. It was implemented in large part by reusing the existing TPOCC software.

Other ECS subsystems support E-mail functions, time services, system administration functions and data base functions. These subsystems were implemented making extensive use of off-the shelf products.

### Physical Architecture

The physical architecture of the EOF had to accommodate the diversity in IWS hardware and operational requirements. It also needed to provide efficient communications between secure and public networks while satisfying security requirements. The SOHO EOF physical architecture is illustrated in Figure 1. Its main characteristics are:

(1) Use of high power workstations able to handle the real-time data rates, while allowing the project scientist and the science operations coordinator to monitor the EOF operations through X-windows and use science analysis software such as IDL.

(2) Use of a high performance router which allows to isolate the ECS and its interface to secure networks from the outside world. It also separates the ECS "operational" data traffic from the IWSs and the data traffic associated with science analysis. Based on predicted data volumes for each instrument team, the IWSs were grouped and connected to the ECS router via seven Ethernet "segments" terminated by hubs and converters. This provides a rather low cost standard connection with all the IWSs. The filtering capabilities of the router are also used to implement network-level security.

(3) Full redundancy: All elements are redundant and data storage is done on a Redundant Array of Inexpensive Disks (RAID).

## APPLICABILITY OF THE EOF TO OTHER MISSIONS

In many aspects, the SOHO EOF had to be customized to the specific requirements of the mission such as restrictive interfaces with other ground system elements and adherence to the pre-existing protocol used in the spacecraft test and integration environment. However, the EOF contains several "building blocks" that are applicable to other missions. In particular, the planning and scheduling subsystem was designed and implemented with reuse in mind. A more detailed description of this subsystem follows.

### Planning and Scheduling Subsystem

The SOHO EOF required a scheduling system to find and resolve conflicts between the individual schedules from each of the satellite's eleven instruments. It had been proposed to reuse an existing scheduling system to support these functions. The EOF new system needed to be flexible, fast and have the capability to merge pre-existing individual schedules. Also, it was to be supplied to several users: the flight operations team within the Command Management System and the instrument teams that wish to use it for planning their own observation sequences. This implied new rules, broad kinds of strategies and activities that the existing system could not support without extensive modifications. This presented the opportunity to re-design and re-implement the scheduling system using object-oriented methods, making it easier to customize and port to different environments: the Planning And Resource Reasoning (PARR) system was developed using an object-oriented design and was implemented in C++.

PARR works as an intelligent tactical planning tool to put specific activities on a timeline by following the strategies and checking constraints found in its knowledge base. PARR's knowledge base consists of a list of strategies used to schedule activities with specific times and durations. One particularity of PARR is that it uses a combination of conflict avoidance and conflict resolution rules; this limits the number of searches required to build a timeline and accelerates the process of building a conflict-free schedule.

The C++ implementation and the use of classes allows to represent abstractions of scheduling objects, such as activities, strategies, resources and constraints Resources include both data that PARR cannot change and data that changes as a result of the schedule it is creating. Activity classes represent types of activity that can be scheduled. Constraints represent PARR's conflict avoidance rules: a constraint can state how an activity must be scheduled in relationship to other activities or resources. Strategies represent PARR's conflict resolution rules: they are used to place activities on the schedule, and to move activities when the constraint checking process discovers conflicts. PARR also uses several paradigms, enabling it to control which activity classes are to be scheduled, the order in which they are scheduled and the merging of schedules created outside of PARR.

Another feature of PARR is that its user interface code has been separated from the algorithmic code, making it easier to adapt to other applications where the user interface is usually the functionality that needs most to be customized to respond a special requirements.

In conclusion, PARR has been designed to facilitate its portability. The object-oriented nature of PARR and its paradigm constructs make it easy to customize for new planning and scheduling applications: for each new PARR application, the classes of generic objects for resource classes, constraints, and strategies can be supplemented with application-specific types.

## CONCLUSION

Overall the development of the EOF has been a success. Costs have been kept under proposed budget. All the initial requirements defined by the scientists have been satisfied, and a few additional capabilities have been implemented without increased funding. The timeliness of the EOF development was highly beneficial to the other SOHO ground system elements: it has provided them with early and precise information concerning the interface with the instrumenters. This aided in reducing risks to the SOHO Project. The basic EOF design is applicable to those missions that requires near-real-time commanding, real-time telemetry distribution, and close communications with the flight operations team. Having the facilities co-located allows cost savings in development, facility operations and maintenance.

The physical architecture of the EOF allows for great flexibility, allowing instrument teams to modify or upgrade their software with minimal impact. It has allowed to implement a sufficient security level while allowing easy communications with the outside world: this is a basic requirement for the scientific success of the mission. Finally its modular software architecture makes the ECS a good candidate for applicability to other missions

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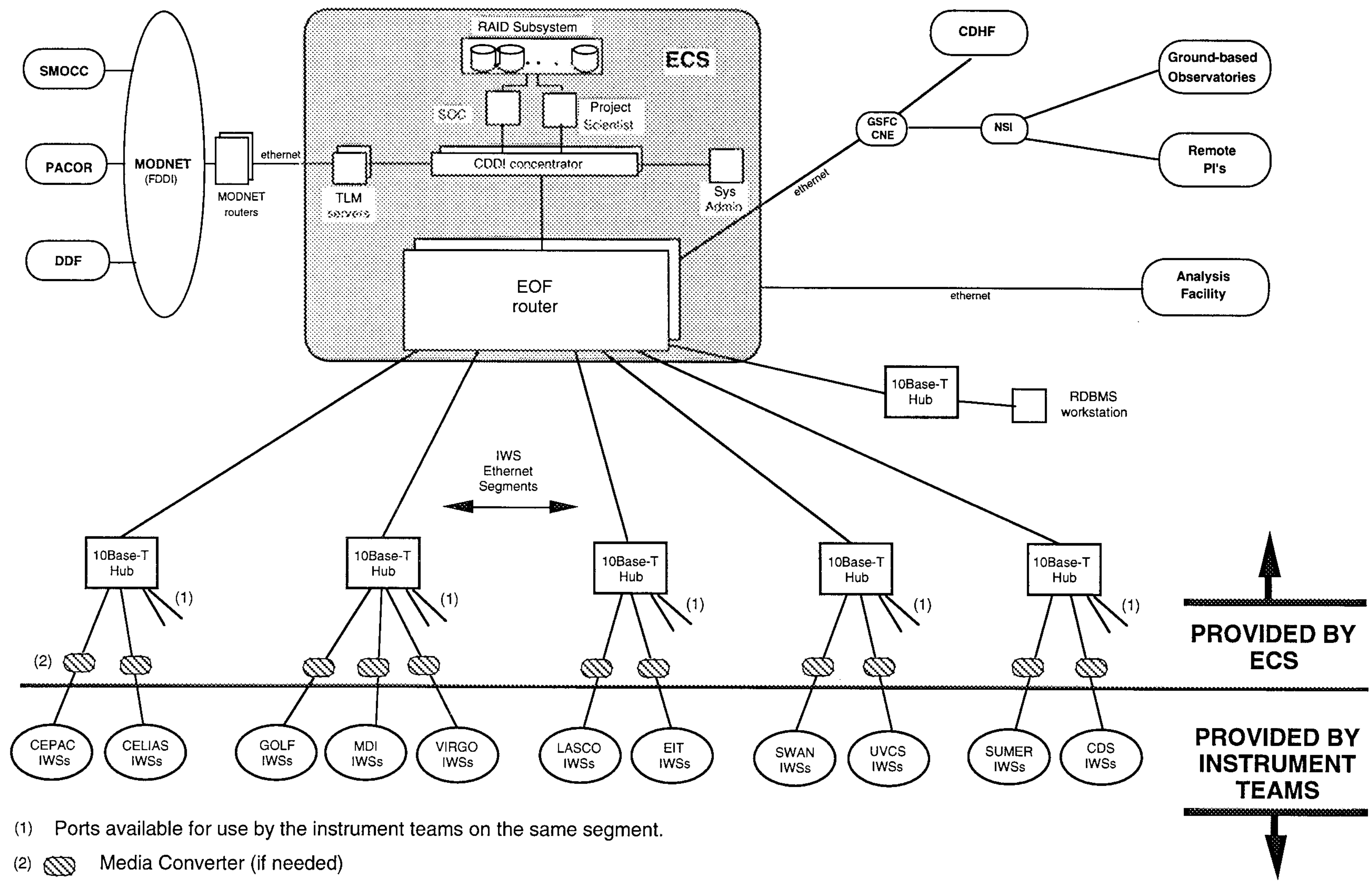


Figure 1. EOF architecture