Ground Data Systems Resource Allocation Process

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Abstract

The Ground Data Systems Resource Allocation Process at the Jet Propulsion Laboratory (JPL) provides medium- and long-range planning for the use of Deep Space Network and Mission Control and Computing Center resources in support of NASA's deep space missions and Earth-based science. Resources consist of radio antenna complexes located in California, Australia and Spain, and associated data processing and control computer networks at JPL. Until 1985, JPL used a manual planning process that was extremely labor intensive and provided a planning horizon of only two to three weeks. With approval of increasingly complex missions, a more efficient planning system was needed to optimize the use of supporting facilities, minimize contention among users, expand the planning horizon to several years and reduce manual labor.

To support an improved planning methodology, a semi-automated system has been developed that not only achieves these objectives but also enhances scientific data return. This end-to-end system allows operations personnel to interactively generate, edit and revise allocation plans spanning periods of up to ten years based on the relative merit of mission events.

An integral part of this system is a software system known as the Resource Allocation and Planning Helper (RALPH). RALPH merges the conventional methods of operations research, rule-based knowledge engineering and advanced data base structures. RALPH employs a generic, highly modular architecture capable of solving a wide variety of scheduling and resource sequencing problems. Because RALPH easily handles generic requirements, the system has had an important influence on the simplification and standardization of input requirements from all projects. Additionally, the system design provides adaptability to changing mission environments.

The rule-based RALPH system has saved significant labor in the resource allocation process at JPL. Its successful use affirms the importance of establishing and applying event priorities based on scientific merit, and the benefit of continuity in planning provided by knowledge-based engineering. The RALPH system exhibits a strong potential for minimizing development cycles of resource and payload planning systems throughout NASA and the private sector.

Resource Allocation Planning at the Jet Propulsion Laboratory

The Ground Data Systems Resource Allocation Process was established at the Jet Propulsion Laboratory (JPL) for the purpose of efficiently managing the use of ground data system resources. These resources include the Deep Space Network (DSN) and the Mission Control and Computing Center (MCCC).

The DSN is a global network of three tracking and data communications complexes which support NASA interplanetary missions and Earth-based science. Each complex has a 70 meter (diameter) antenna, two 34 meter antennas, and a 26 meter antenna. The four antennas are linked to a Signal Processing Center computer network at each complex. Each of the three Signal Processing Centers is linked by high-speed and wideband circuits to the MCCC data systems residing at JPL.

The MCCC is a centralized multimission data processing and control center. It has the resources required for the successful conduct and control of all aspects of space flight missions and radio-based astronomical observations. These include performing real-time multimission operations, data processing and systems control, and non-real time computations, such as image processing and data records generation.

The JPL Flight Project Support Office (FPSO) is responsible for allocating DSN and MCCC ground data system resources for spacecraft tracking, communications and science activities. The output of the resource allocation process is plans for optimal use of the available system resources. These plans must support the requirements of all missions. As a minimum, survival support must be guaranteed to spacecraft whose missions have been granted extensions beyond their primary objectives.

Understanding Planning Constraints

Allocation plans are required to address the needs of all projects, each of which may be in different phases of their lifecycles: missions in flight, in pre-flight development or in advanced planning stages. Allocation plans must be based on a set of constraints consisting of viewperiods, project requests, and system resource requirements. Each of these constraints is affected by dynamic factors that influence the planning strategy from week to week, complicating the planning problem.

A viewperiod is a time interval over which a spacecraft is in view of a particular station antenna, allowing tracking and communications with the spacecraft. The ground stations are spaced at intervals of about 120 degrees in longitude from one another, ensuring that a spacecraft will be in view of at least one ground station at any time as the Earth rotates. Thus, each antenna at a single complex will have a viewperiod for each spacecraft target at least once during each Earth rotation. The dynamics of each spacecraft flight path determine the exact time and duration of every viewperiod.

Project requests come in two different forms. There are specific requests and generic requests. Specific requests cover critical, time-dependent events. Projects typically demand specific tracking coverage to compensate for restrictions imposed by viewperiods or flight paths. A planetary encounter is one such time-dependent event. This level of input severely reduces planning flexibility.

Generic user requests tend to be non-time dependent. A project user will ask for a total amount of support and a broad class of equipment over an extended time period. An example is the minimum antenna coverage necessary to ensure signal reception. Combinations of antennas may be required to pull in very distant signals. Minimum and maximum allowable activity separations is another typical requirement. At the most general level of input, a user requests the fulfillment of project objectives within a specific time frame. Such generic requests afford the most latitude in planning equipment allocations for a particular window of time.

System requirements place another set of constraints on the resource allocation process. Certain station equipment must undergo pre- and post-calibration. Station crews typically require a minimum of half an hour separation between successive signal acquisitions to make these necessary configuration changes. Resource maintenance, downtime and unmanned periods also contribute to the complexity of the planning problem.

The Resource Allocation Problem

From the inception of the Deep Space Network in 1958 through early 1986, resource allocation was essentially a manual process. Even for typical tracking situations, planning is a complex problem with many variables. The high level of complexity dictates that the solution be determined in a somewhat non-systematic way that usually involves a great deal of human decision. In a joint effort with the DSN, MCCC, Flight Projects, and other users, FPSO established several teams to accomplish the goals of the resource allocation process.

The Joint Users Resource Allocation Planning Committee (JURAPC) includes the managers and scientists of all involved organizations. It functions to establish allocation policies and priorities and to review proposed support requirements, established plans, and requests to modify requirements.

The Resource Allocation Planning Team (RAPT), a subcommittee of the JURAPC, is chartered to implement established policies, gather support requirements, review resource allocation plans, establish event priorities and resolve conflicts through negotiations. The RAPT is the focal point for all contention studies and "what-if" feasibility studies.

The Resource Analysis Team (RAT) consists of expert planners and analysts. The workhorse of the resource allocation process, it operates and maintains the tools necessary for production of plans and special studies, and for database administration. The RAT team leader also coordinates and mediates all RAPT meetings.

Using the manual planning system, this labor-intensive approach to resource allocation was capable of

providing a planning horizon of only two to three weeks. The lack of a structured method for determining feasible support led to the generation of allocation plans which did not adequately reflect user needs. As a result, many hours of negotiations per week were necessary in order to clear unforseen conflicts.

Over the years, the number of approved missions has been growing and their data collection and transmission capabilities have been expanding. Compounding the problem, most of the DSN-supported spacecraft have proceeded in the same general directions away from Earth, causing viewperiods to overlap considerably. Because of this overlap, the concentration of requests for resources has caused an uneven allocation profile. It became imperative to develop a more efficient planning system to optimize the use of supporting facilities, minimize contention between users, expand the planning horizon to several years, and reduce manual labor.

Development of a Software Tool

JPL established a Design Team to develop a tool that gives the Resource Analysis Team the ability to achieve a more efficient planning system. This Design Team joined planning analysts and software developers in an environment that enhanced information exchange (Figure 1). This integration of operations and development provided a global view of the task. Operational goals and developmental capabilities were merged to create a software tool that assists in all facets of the resource allocation process. It was named the Resource ALlocation Planning Helper, or RALPH. The relationship of RALPH to the resource allocation process is illustrated in Figure 2.

The Design Team established clear top-level goals for the RALPH system:

● Generation of detailed resource allocation plans
● Reduction of plan generation time
● Reduction of user conflict negotiation time
● Quick turn-around for special studies
● Automation of resource selection
● Allocation based on event prioritization

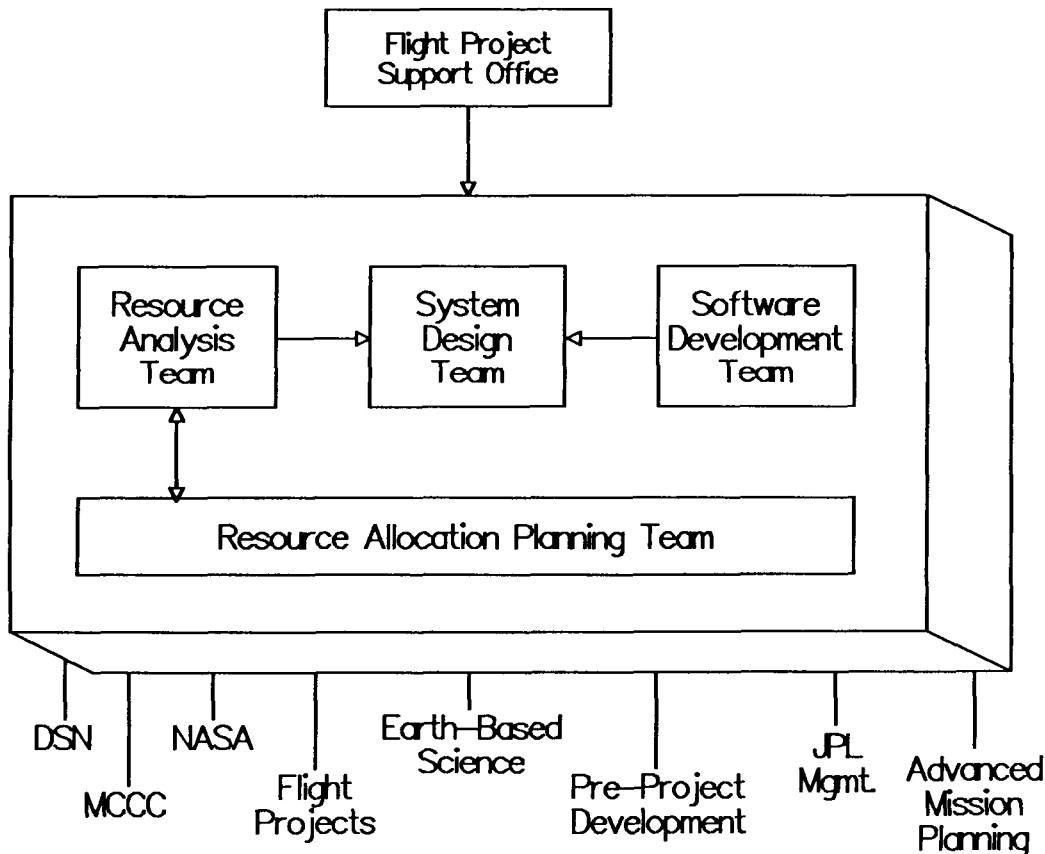Important new concepts were introduced to optimize resource planning:

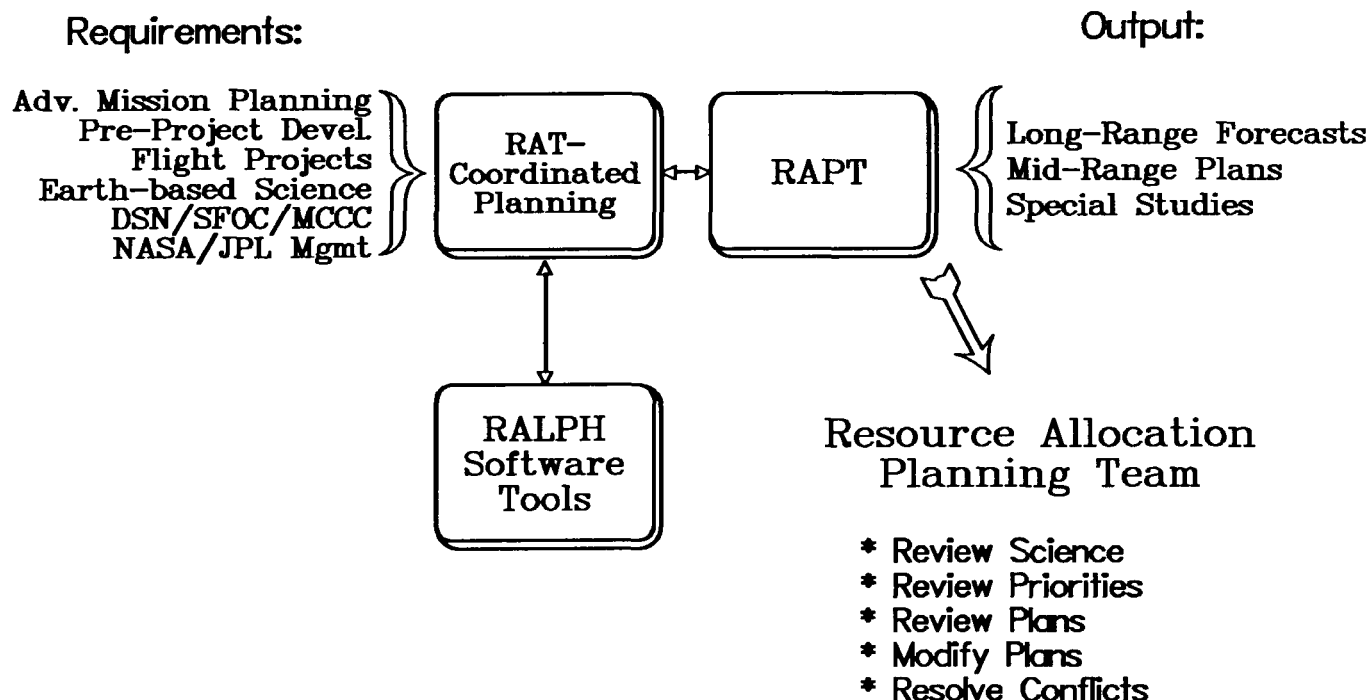Figure 1 — JPL Resource Allocation Planning Environment

Requirements:

Adv. Mission Planning
Pre-Project Devel.
Flight Projects
Earth-based Science
DSN/SFOC/MCCC
NASA/JPL Mgmt

Output:

Long-Range Forecasts
Mid-Range Plans
Special Studies

RAT-
Coordinated
Planning

RAPT

RALPH
Software
Tools

Resource Allocation
Planning Team

* Review Science
* Review Priorities
* Review Plans
* Modify Plans
* Resolve Conflicts

Figure 2 — JPL Mechanism of Resource Allocation

● Maximization of science return, followed by optimization of resource utilization

● Identification of the variance between resource allocation plans and the sum of the original requirements (e.g., NASA Support Plans)

Implementation of these concepts would enable the planning analysts to better manage the resource allocation process and improve internal flight project planning and scheduling processes. Previous allocation techniques have been based on mission priority. Planning analysts at JPL have pioneered the idea of levels of support based on scientific merit or "event" priority. This method gives project negotiators a clear understanding of the impact on science return caused by any compromises to the plan.

It is a goal of the resource allocation process to create 100% conflict-free resource allocation plans. However, oversubscription of resources, as well as the viewperiod overlap problem, creates a situation such that requests can not be completely satisfied. RALPH allows the resource analysis team to provide project users with near-optimum resource allocation plans which meet all user requirements while clearly pinpointing any remaining conflicts. It remains a human decision-making task for project users to jointly negotiate a final determination of acceptable conflict-

free levels of support. The final product is then used for mission operations schedules.

Accommodating the Project Lifecycle

The resource allocation process was designed to accommodate project needs throughout the various phases of their lifecycles. For this reason the resource allocation process provides products for three distinct subprocesses:

● Special studies
● Long-range forecasting
● Mid-range planning

Special studies are generated throughout the project lifecycle. Approximately ten years before a proposed spacecraft launch, when a new project defines preliminary functional requirements for spacecraft design and equipment support, the Resource Analysis Team reviews those requirements in light of approved resource allocation plans and major events. These special studies provide valuable impact assessments early in the project lifecycle.

At any time, projects may request special studies to assess the feasibilities of different planning options, such as the impact of moving spacecraft launch windows. If contention appears inevitable, it is identified

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within the report, along with appropriate statistical analyses and recommendations for alleviating the conflict.

Between two to ten years before a project's launch, the feasibility of requirements is seriously considered. This is the first point at which all requirements, such as the Support Instrumentation Requirements Document, the NASA Support Plan and the Mission Support Plan, are brought together and considered in total. At this stage, the requirements contain sufficient detail to generate a resource allocation forecast. However, the information during this period is tentative and subject to change based on many different factors. Despite their tentative nature, these long-range forecasts provide valuable resource allocation overviews during the mission's planning phase. Forecasts assist in the process of enhancing science return and reducing user impact. In addition, they supply information that is instrumental to advanced planning and resource loading studies.

Mid-range planning occurs between eight weeks to two years before an event. The resource allocation phase of the project lifecycle occurs from two years to six months prior to an activity. During this period, resource allocation plans are provided to project users for mission sequence development. This period marks the beginning of the iterative human decision-making process of conflict resolution between all project users,

conducted by the Resource Analysis Team in RAPT and JURAPC meetings.

Between six months and eight weeks before a planned activity, all conflicts must be resolved. This period supports the operations phase of the project lifecycle. At eight weeks prior to launch, the DSN and MCCC are presented with detailed conflict-free resource allocation plans for real-time operations. Figure 3 is an overview of the resource allocation process.

Certain products were identified to support each phase of the allocation process. These were selected as output candidates for the RALPH system design.

Special Studies
  ● Impact studies
  ● Management overviews

Long-Range Forecasting
  ● Detailed long-range forecasts
  ● Summaries and supporting analyses

Mid-Range Planning
  ● Detailed resource allocation plans
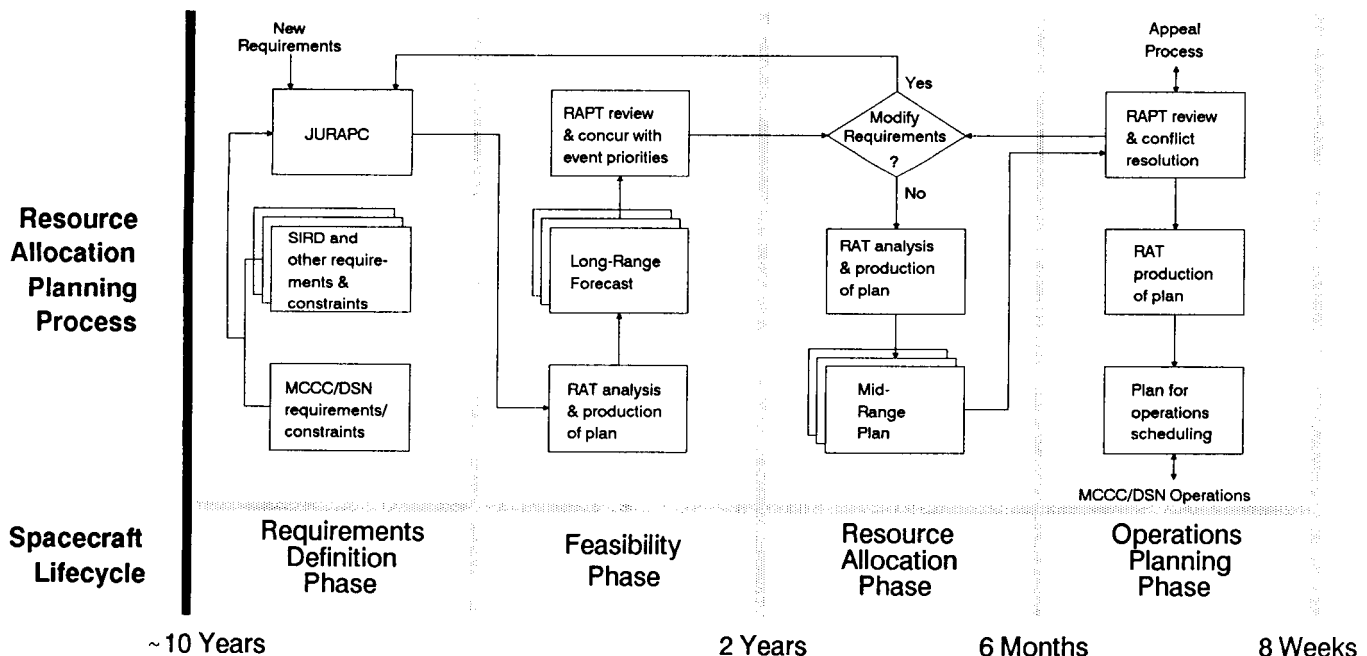 ● Conflict summaries
  ● Resource loading summaries

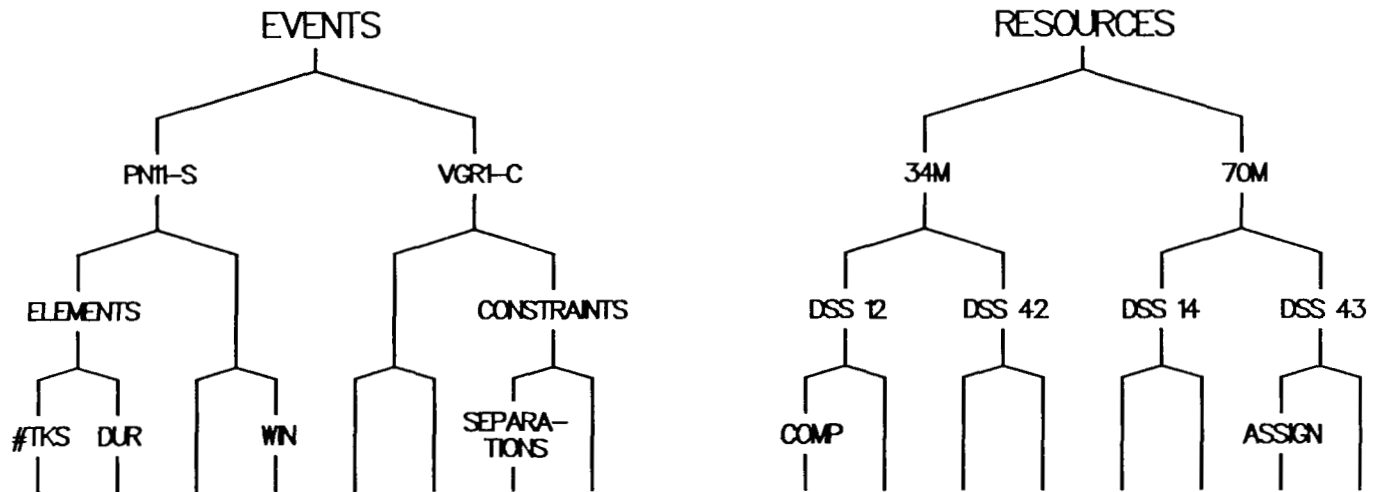Figure 3 — JPL Ground Data System Resource Allocation Process

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Figure 4 — Hierarchical Tree Structure of Data Representation

With top-level goals and products clearly defined, the next step was to model the processes of the resource allocation problem.

Modeling Resource Allocation

RALPH is implemented as an expert system that utilizes hierarchical tree structures. These tree structures contain descriptions of resources, requirements and specific rules. Data within these structures are easily modified to represent new conditions (Figure 4).

The formal analytical processing capabilities of Operations Research (OR) have been included in modules that solve problems of resource allocation. Other modules include rules for attribute assignment, constraint violation, event language entry, and syntax parsing of user support events. All of these modules form a generic section of code, called the Core Resource Allocation Modules (CRAM). Each CRAM module is designed to utilize the symbolic logic and predicate calculus of the tree structures. In this way, the synthesis of knowledge engineering and OR technologies has proven to be a successful solution to the JPL resource allocation problem.

The entire resource allocation problem can be decomposed into five functional steps. This five-rule set, initially proposed by Information Sciences, Inc. in the 1970's, provides a paradigm of the way a human analyst solves an allocation problem. The steps are:

1. Definition of user support goals and feasible support descriptions
2. Prioritization of feasible support
3. Resource assignment
4. Time assignment
5. Plan verification and conflict resolution

The five-rule set suggested the need for several software subsystems to support the resource allocation planning function. These subsystems, a requirements translator, a mid-range plan generator, a long-range forecast generator, text and graphics editors, and an output capability generator are linked to provide a linear data flow through the system (Figure 5).

The requirements translator is a high-level language processor. User event support descriptions are entered through language syntax processing modules which prompt the operator for appropriate attribute entries. The event description syntax is stored as a string. User support events may have attributes such as duration of assignments, resource preferences, and temporal relationships.

Priorities are assigned based on the scientific significance of the user events. This concept was originated by the Resource Allocation Planning Team as the best means of achieving maximum science return with limited data system resources. The priority system, depicted in Table 1, is applied to all users for planning purposes. In this numerical scheme, an assignment of "one" represents the highest priority.

The plan and forecast generator subsystems parse syntax strings into standard event tree structures. The generator must then allocate resources and time to those events that are consistent with the resource assignment objects contained within the system under the following guidelines:

- Fully satisfy each user event
- Minimize conflict among users
- Maximize resource utilization

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To reduce the combinatorial complexity that is typically encountered in large-scale resource scheduling systems, the generator uses a two-pass approach. The first pass determines probabilistic profiles of resource usage determined by requirements, windows and hard constraints. The second pass uses these profiles to evaluate possible scheduling points for minimum conflict. It proceeds in order of event priority, transforming the probabilistic profiles into deterministic schedules.

Finally, RALPH employs two types of resource assignment editors for plan verification and conflict resolution. Change entries are verified by many of the same CRAM attribute validation modules used by the requirements translator for event object descriptions.

When validating and enhancing allocation plans, planning analysts may use the RALPH graphics editor. This allows easy modification of the plan based on operator recognition of color-coded visual allocation patterns (Figure 6).

Modifications may also be entered through the RALPH text editor. This editor is designed to mimic the manual paper process used in RAPT negotiation meetings. It consists of line listings of resource allocations sorted by day of week, time and user. The paper-based process will soon be eliminated entirely in favor of computer-aided editing.

Results

The RALPH software is implemented on a DEC MicroVAX II customized with a GPX high-resolution graphics workstation. RALPH is fully operational, allowing the Resource Analysis Team to efficiently produce long-range forecasts and mid-range plans for the DSN and MCCC. The number of workhours required to produce a one-week mid-range plan have been reduced from 25 hours of manual labor to five hours using the RALPH tool. Without RALPH, long-range forecasts were not possible. With RALPH, long-range forecasts have been enabled.
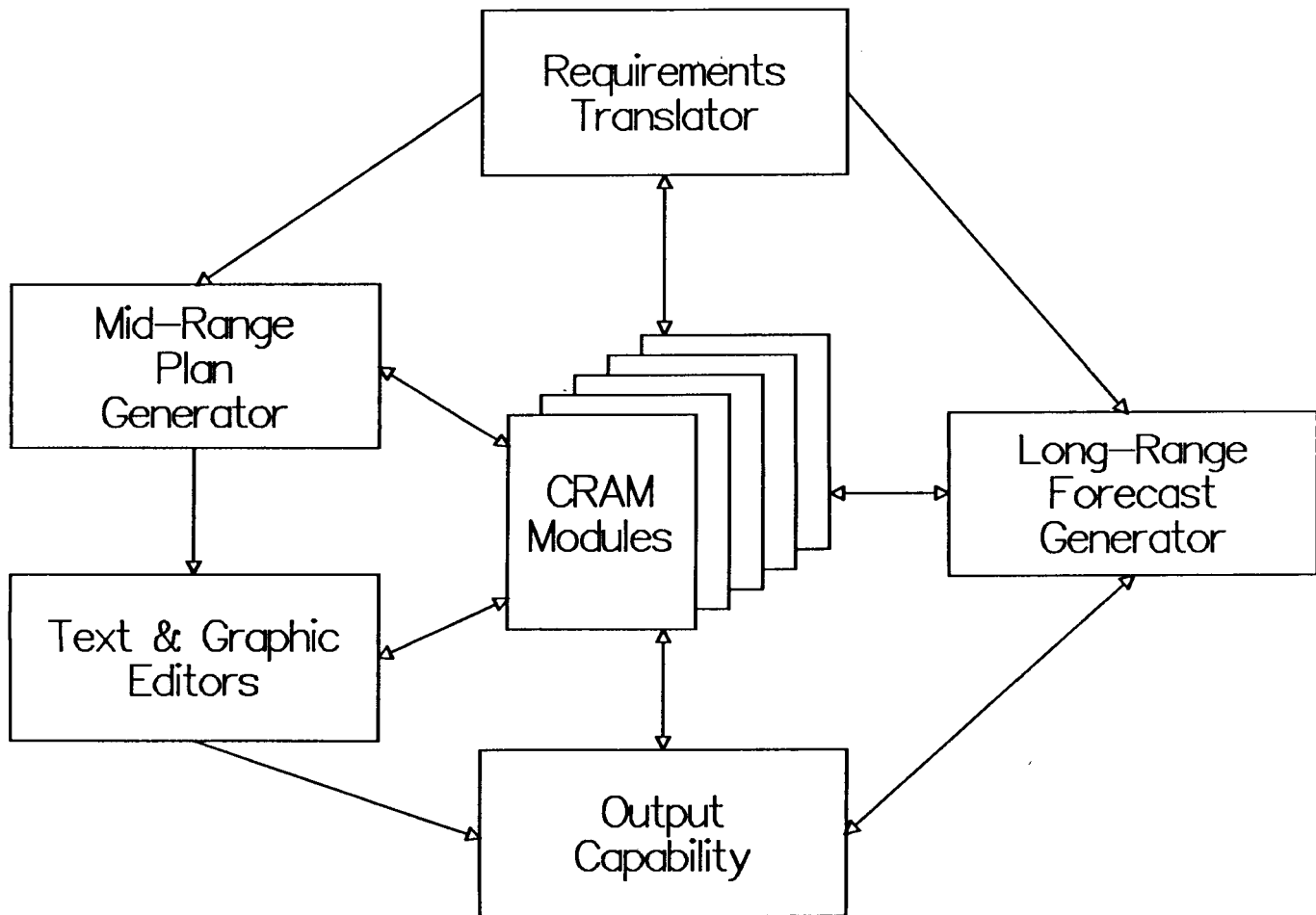

Figure 5 — RALPH System Architecture

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Table 1 — Definitions of Resource Allocation Event Priorities

Priority	Activity Period and Priority Criteria*	Examples**
1	Spacecraft Emergency which Threatens Achievement of Primary Objectives Time Critical	Determined in Real Time
2	Single Opportunity or One-time Event Manditory for Achievement of Primary Objectives Time Critical	Launch Midcourse Maneuvers Planetary Near Encounter Some Scientific Events**
3	Irregular Events with Subsequent Opportunity Available Mandatory for Achievement of Primary Objectives Time Critical	Trim Maneuvers Some Orbital Cruise** Some Interplanetary Cruise** Planetary Radar
4	Regular or Repeated Events Mandatory for Achivement of Primary Objectives Time Critical	Telemetry Dumps Some Interplanetary Cruise** Some Orbital Cruise**
5	Not Mandatory for Achievement of Primary Objectives Time Critical	Extended Mission Some Interplanetary Cruise** Planetary Radio Astronomy Some Orbital Cruise**
6	Mandatory for Achivement of Primary Objectives Not Time Critical	Some Orbital Cruise** Some Interplanetary Cruise** Pulsar Rotation Constancy
7	Not Mandatory for Achivement of Primary Objectives Not Time Critical	"Priority-6" for Extended Mission

*These criteria are subject to revision by the RAPT, but they have not been revised for a number of years.
**Actual events as governed by the priority criteria would, of course, be more project-specific.
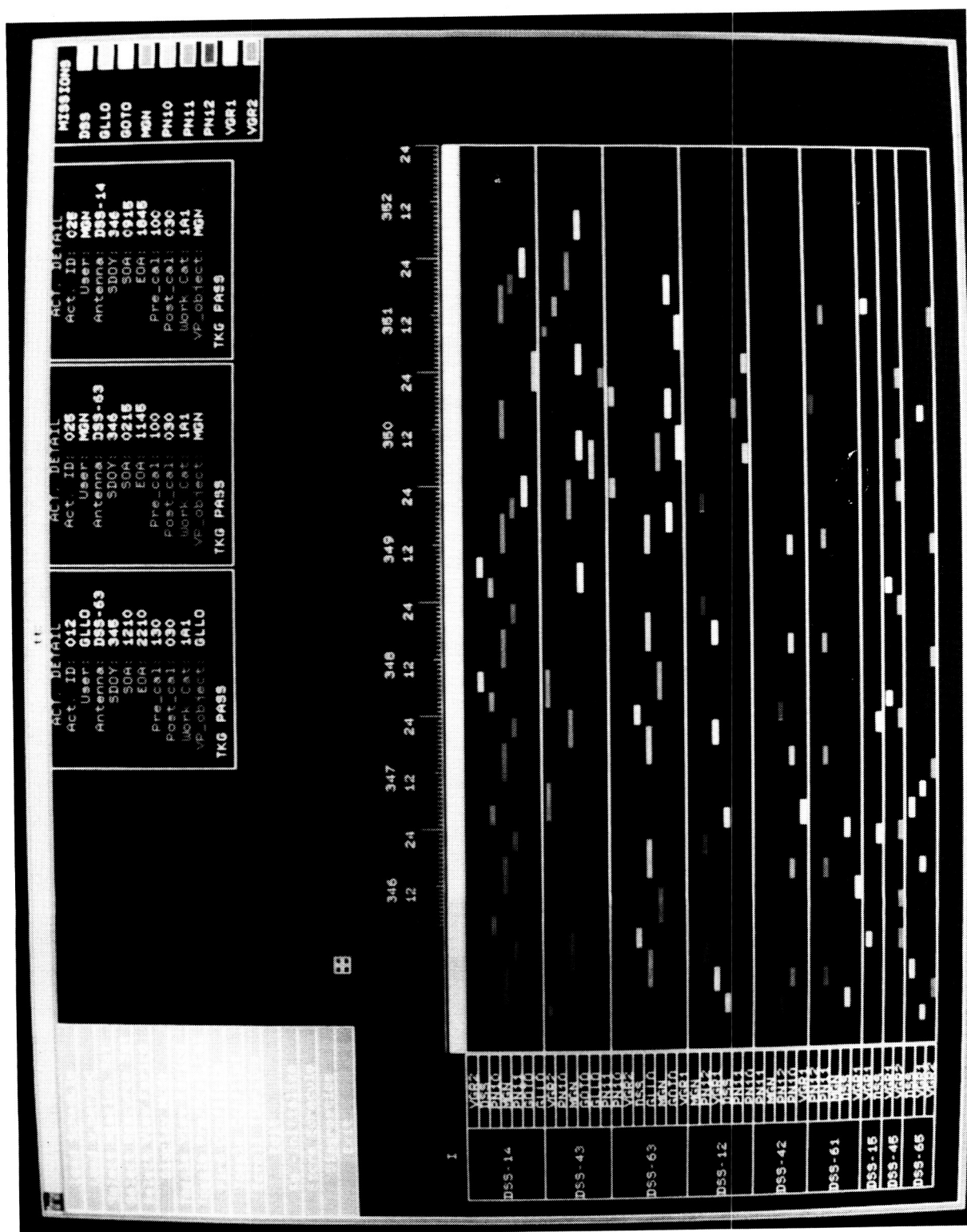
Figure 6 — The RALPH Graphic Editor Allows Interactive Fine-tuning of Plans

Table 2 — Results from RALPH Implementation

Item	1986	1989
Mid-range plan	25 hours	5 hours (Savings: 1040 hrs/yr)
Meetings per week	3-4	1 (Savings: 6240 hrs/yr)
Planning horizon	3 months	10 years
Long-range forecast	Impossible	Possible
User interface	Informal	Standardized
Requirements	Specific	Generic
Data dissemination	Manual	Electronic
Quick-look studies	Very difficult	Now doing one/week

The RAPT meetings have benefitted as a result of more efficient output products. Previously, three to four negotiation meetings were required each week to clear conflicts. The research process of formalizing the event model led to a well-defined interface structure between resource users and operations personnel. Even without any software implementation, this increased definition has led to a significant reduction in requirements generation and negotiation time among users. The addition of the RALPH tool has further reduced the conflict level to the extent that one meeting per week is sufficient (Table 2).

There are several key factors that contributed to the successful implementation of the automated software tool. The formation of a Design Team, which merged operational users and software developers, was a catalyst for a better global understanding of the functionality that is the core of the resource allocation process. The merging of knowledge engineering and operations research methodologies, with the application of the five-rule paradigm, clearly defined the operational environment. All of these factors resulted in the creation of effective software.

The RALPH software is highly data driven and modular. These features, combined with the generic designs of the data structures, make the RALPH system extremely easy to modify. Object attribute representations are readily updated by operations personnel to reflect a changing resource environment without modification of the programs that use the data. The data structure and software modularity enable RALPH to cross problem boundaries and support related tasks with minimal development effort. These features enable the Resource Analysis Team to respond quickly to requests for special studies and management reports. A typical statistical report output from the RALPH system is depicted in Figure 7.

The evolution provided by the RALPH system from a forecast to an operational plan has provided an efficient utilization of limited ground data system resources. RALPH has affirmed the significance of establishing and applying event priorities based on scientific merit and the benefit of continuity in planning provided by knowledge-based engineering. RALPH is designed as an expandable system to meet the needs of an evolving allocation process. With appropriate emphasis on problem understanding and representation, the same methodologies merged to build RALPH can be utilized to support a large class of resource allocation and planning systems. The RALPH system exhibits strong potential for minimizing development cycles of resource and payload planning systems throughout NASA and the private sector.

Reference

Craig D. Johnson and David G. Werntz, "A New Methodology for Resource Allocation and Planning", International Space Conference, Johnson Space Center, Houston TX, November 17, 1987.

Acknowledgements

About the Authors

Carol A. Berner is the Cognizant Operations Engineer of the Resource Analysis Team. Her nine years of experience at JPL cover many aspects of telecommunications and space flight operations. A member of IEEE, she has a B.S.E.E. from the University of California at Los Angeles, and is currently working on an M.S.E.E. specializing in the field of Intelligent Systems at the University of Southern California.

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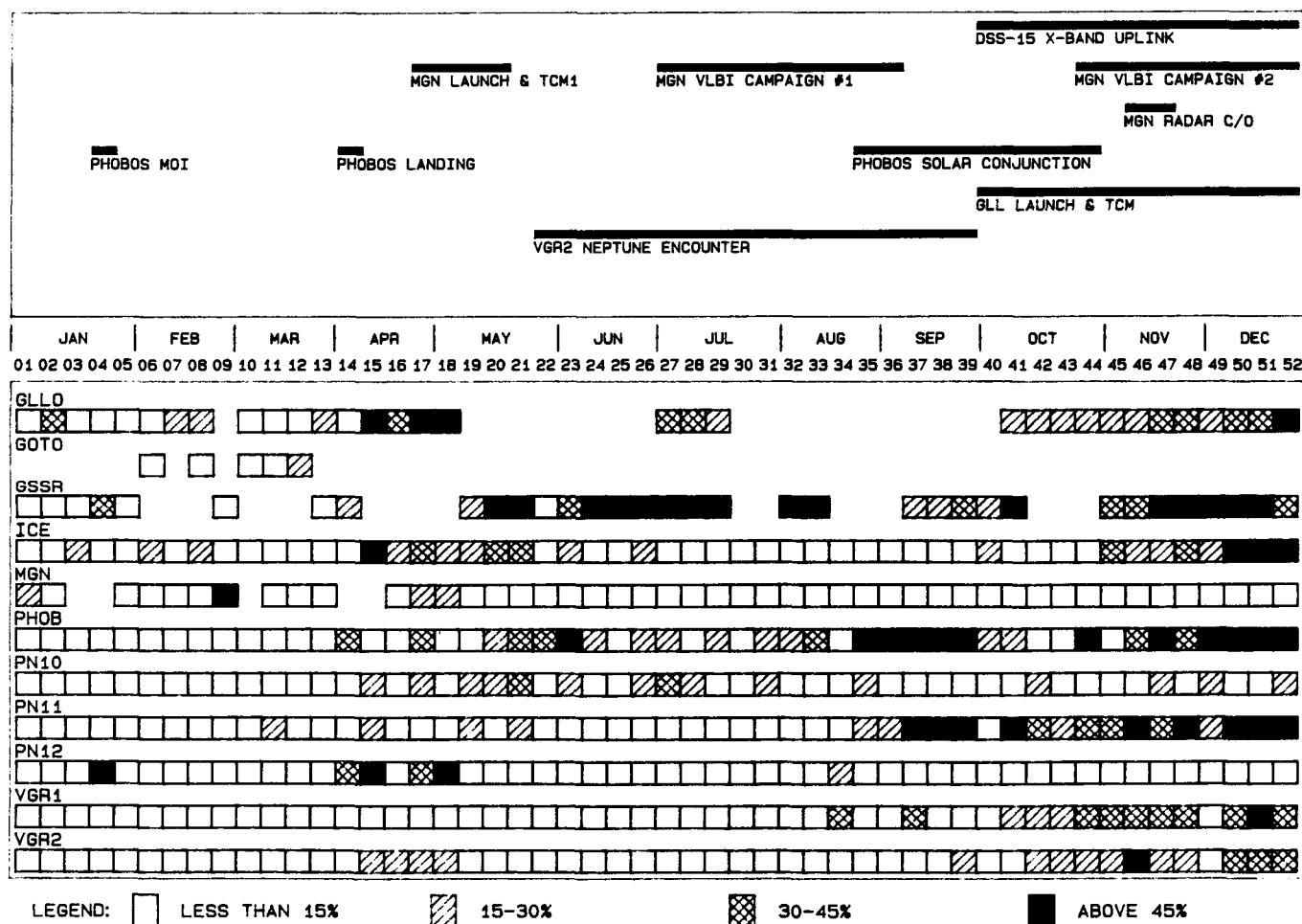
Figure 7 — Example of output: contention by user