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Intelligent Perturbation Algorithms for Space Scheduling Optimization

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Abstract - The limited availability and high cost of crew time and scarce resources make optimization of space operations critical. Advances in computer technology coupled with new iterative search techniques permit the near optimization of complex scheduling problems that were previously considered computationally intractable. This paper describes a class of search techniques called Intelligent Perturbation Algorithms. Several scheduling systems which use these algorithms to optimize the scheduling of space crew, payload and resource operations are also discussed.

Using Heuristics for Optimization

The development of techniques to solve scheduling problems has historically centered around the investigation of idealized scheduling models which were often simpler than problems typically encountered in the real world.[4, 6, 13] Except for the simplest models, scheduling problems can be described mathematically as "NP-Hard."[3, 14] All known mathematical techniques for finding optimal solutions to NP-Hard problems are too slow to solve realistically large problems.[15]

In practical applications, heuristic techniques are often used to solve problems which are otherwise intractable. Heuristics usually produce solutions of good quality but do not always find the most optimal solution. Whereas the computational difficulty of finding the exact optimum solution increases exponentially as a function of the size of an NP-Hard scheduling problem, with heuristic algorithms the difficultly of finding "quasi-optimal" solutions usually increases only in a polynomial fashion. Polynomial heuristic algorithms can therefore find solutions to realistic problems in a computationally feasible search time.

In some cases, heuristic techniques can be shown to produce solutions which have desirable properties such as guaranteeing to always be within a certain percent of the optimal solution. For more complicated problems, however, even these guarantees may not be possible. In the case of many space related scheduling problems, the optimization criteria can be inexact and the data base (e.g., estimates of the expected time necessary to complete an activity) may be uncertain; hence, a heuristic can be considered successful if it can be applied to a set of test problems and shown to consistently produce schedules which are nearly optimal. With confidence in such a heuristic it could then be applied to larger and more complicated problems for which finding the optimum is not realistic. Additionally, having a heuristic which can compute a solution on a time scale fast enough for the solution to be used immediately (as would be necessary to perform real-time replanning) is superior to producing a nominally better solution which cannot be obtained in real time.

Intelligent Perturbation Algorithms

A typical scheduling problem involves the placing of activities onto a timeline while respecting constraints which may restrict the times at which the activities many be performed and the resources available for the activities to use. A grading function is established to judge the relative merits of different schedules.

Intelligent Perturbation Algorithms are heuristic techniques that have been developed by the author for the quasi-optimization of complex scheduling problems. These algorithms iteratively search the combinatoric solution space just as techniques such as gradient search are used for solving continuous domain optimization problems. Like other iterative search techniques such as Simulated Annealing Algorithms[1, 5, 7, 16] and Genetic Algorithms[17, 18], Intelligent Perturbation Algorithms iteratively examine (and make perturbations upon) successive schedules in an attempt to find a progressively better solution. Unlike these other techniques (which search in a more random fashion), Intelligent Perturbation Algorithms use a strategy that considers both the structure of the problem's constraints and its objective function to decide how to modify a schedule to increase the likelihood that the next perturbation will yield a more optimal solution.

To create an initial schedule (the first iteration), a method is devised to generate a ranking of all unscheduled activities, and then the highest ranked activity is added to the timeline. The procedure is then repeated to select the activity with the next highest ranking, adding it to the timeline. This continues until all the activities (or as many as possible) have been added to the schedule. The particular method used to initially rank the activities and the specific way in which activities are added to the timeline are not pertinent to the general operation of the Intelligent Perturbation Algorithm.

Following this first iteration, the rankings of the activities are adjusted using a problem specific procedure called a perturbation operator. These new rankings are then used on the next iteration to produce another schedule which is hopefully of superior quality (as measured by the grading function). This process then repeats for subsequent iterations until a cutoff criteria is reached. The best schedule found during the course of the search is then recalled.

Emperical experience has shown that good perturbation operators share many characteristics:

1) The operator should increase the rankings of an activity or activities which were not satisfactorily scheduled during the previous iteration. The operator should also increase the rankings of "bottleneck" activities (which may have been successfully scheduled) that prohibited the satisfactory scheduling of other activities due to temporal constraints linking those activities to the bottleneck activity.
2) The operator should be able to potentially span the search space in a small number of steps.
3) The computational overhead of computing the perturbations between each iteration should be small compared to the computational cost of producing a single schedule. Extensive testing has shown that by looking at many good schedules, Intelligent Perturbation Algorithms are likely to find a very good schedule in a reasonable number of iterations. There is a greater payoff in searching through more schedules than in investing a great deal of computation in the perturbation operator. This is consistent which the strategy employed by the best chess playing computer programs which achieve their skill by searching through a large number of positions rather than through the use of strategy.
4) The perturbation operator should have a random component (or some other provisions) for avoiding loops and getting trapped near local optima.

For many space operations, the costs of opportunities which are lost due to inefficient scheduling can easily amount to millions of dollars per week. The proper design of the perturbation operator is critical to the success of the Intelligent Perturbation Algorithm, and will vary for different types of scheduling problems. The specific details can be considered proprietary; as the utilization of space becomes more commercial, the possession of good perturbation operators can provide a capability to operate more efficiently and thereby bestow a competitive advantage.

Intelligent Perturbation Algorithms can be made flexible enough to accommodate a large range of problem structures including highly complicated constraint environments which could not be addressed by previous heuristic optimization methods. The search inherently focuses on the complicated parts of a scheduling problem while it avoids dealing with factors which are not present in a particular problem instance.

Figure 1 shows results of using the Intelligent Perturbation Algorithm, averaged over many test problems.[10] In each problem, the objective was to generate a timeline which allowed completion of a set of time and resource-constrained activities as early as possible. Using non-iterative heuristic techniques standard in operations research literature, solutions were found which averaged about 23% longer than optimal; after 10 search steps using an Intelligent Perturbation Algorithm, average schedule quality was improved to within 10% of the optimum, a significant improvement. After 100 search steps, the average schedule quality was improved to only 7% longer than the optimum. Usage on many different problems has shown that while the scaling of the axes will vary for different types of scheduling problems, the general character of the "learning curve" relating schedule quality to the number of iterations remains largely unchanged.

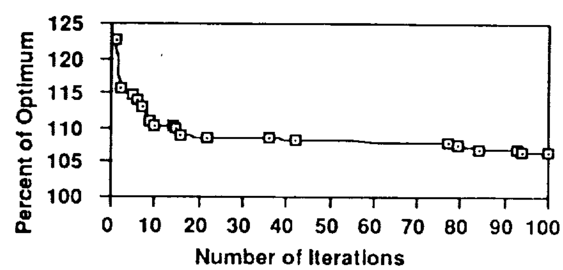

Figure 1: Solution Improvement with Iteration Number

Intelligent Perturbation Algorithm Applications

Aerospace systems have been developed which apply Intelligent Perturbation techniques to the scheduling of crew, payloads, and resources aboard space-based systems. Space Industries is examining the application of Intelligent Perturbation Algorithms beyond the aerospace industry into diverse areas such as the optimization of petrochemical plant operations and the scheduling of medical operating rooms. Additionally, an independently developed iterative refinement methodology, called chronology-directed search, has been developed at JPL and is being applied to the scheduling of deep space missions.[2]

Space Station Scheduling

Aboard the International Space Station *Freedom*, crewmembers would benefit from having the capability to participate in the scheduling of their own activities. To address this need a prototype interactive software tool known as the MFIVE Space Station Crew Activity Scheduler and Stowage Logistics Clerk was developed at the Space Systems Laboratory of the Massachusetts Institute of Technology (MIT).[10, 11, 12] MFIVE (Figure 2) provides a user friendly interface for building, solving and displaying scheduling problems as well as for investigating the features which will be necessary to provide a real-time scheduler for use aboard *Freedom*.

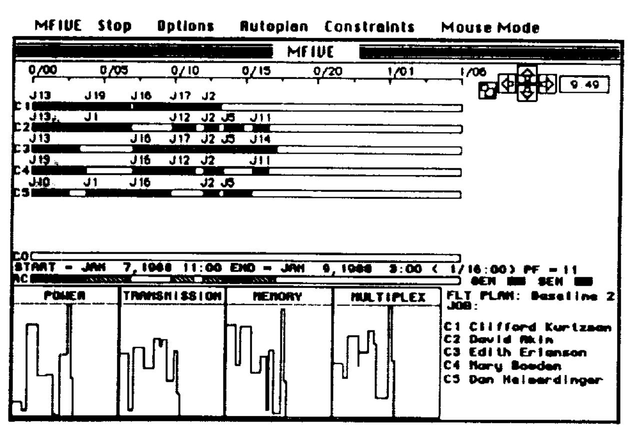

Figure 2: MFIVE Space Station Scheduling Worksheet Showing Task Assignment and Resource Usage for Five Crewmembers

MFIVE was not intended to provide a fully robust model of the realistic Space Station environment but rather to demonstrate some of the features which will be necessary to support development of actual Space Station planning and scheduling tools. While the MFIVE system was created to deal primarily with manned activities, it is also capable of dealing with unmanned operations. First prototyped in 1986, MFIVE was used to develop and test the initial implementations of the Intelligent Perturbation Algorithm. MFIVE also demonstrated user-friendly features such as graphics, windows, menus and a mouse-driven interface on a low cost Macintosh desktop computer.

MFIVE is currently being used by the MIT Man-Vehicle Laboratory to examine scheduling scenarios for the Spacelab SLS-1 and IML-1 life sciences pre/postflight baseline data collection facility. These data collection sessions provide control data to compare against data collected on-orbit and measure post-mission readjustment to earth's gravity.

Another optimization tool using the Intelligent Perturbation Algorithm has been developed to support work being done for the Space Station Program Support Contract for the scheduling of Space Station Design Reference Missions (DRMs). Scheduling of DRMs involves generating demonstration timelines for Space Station crew and payload operations at selected periods during the lifetime of the Space Station. As shown in Figure 3, schedules have been generated which show significant improvements over schedules produced with standard scheduling tools, both in terms of resource utilization and in the accomplishment of mission priorities.[8] The analysis of this DRM required the scheduling of 422 requested operations of 74 payloads over a two week period. Three resources were considered: crew, power, and the availability of a high quality microgravity environment. Assuming a rate of $100,000 per IVA crew-hour (as called out by NASA in its recent request for proposals for the Commercial Middeck Augmentation Module), the optimization analysis saved 5.3 million dollars per week in opportunity costs that would have otherwise been lost through inefficient scheduling.

DRM 4 - Command & Control Zone Operations/Man-Tended Free Flyer Servicing	Payload Runs	Crew-Hours Scheduled
Requested	422	539 hr, 10 min (118.1%)
Available	N/A	456 hr, 30 min (100.0%)
NASA Provided Baseline	272	333 hr, 35 min (73.1%)
Space Industries Result	387	440 hr, 10 min (96.4%)

Figure 3: DRM 4 Resource Utilization Optimization

Industrial Space Facility Scheduling

The ability to provide flexible manifesting and scheduling is critical to the operation of the Industrial Space Facility (ISF), a man-tended free-flying space platform being developed by Space Industries for launch in the 1990s. The ISF has been designed to serve as a bridge to the Space Station era, providing a high-power, low-gravity environment for conducting microgravity research. A software tool called the Prototype ISF Experiment Scheduler has demonstrated that efficient and cost-effective operation of the ISF is possible through the use of multi-variable optimization techniques based on the Intelligent Perturbation Algorithm.[9] Figure 4 (next page) shows resource utilization profiles for an optimized 100 day ISF mission. The objective function was based largely on maximization of power utilization.

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Bibliography

[1] Berman, D., McClure, J.W., "A Comparison of Scheduling Algorithms for Autonomous Management of the Space Station Electric Energy System." AIAA Guidance, Navigation and Control Conference, August 1987. AIAA-87-2467.

[2] Biefeld, E.W., and Cooper, L.P., "Scheduling with Chronology-Directed Search." AIAA-89-3137, AIAA Computers in Aerospace VII Conference, October 3-5, 1989.

[3] Blazewicz, J., Lenstra, J.K., Rinnooy Kan, A.H.G., "Scheduling Subject to Resource Constraints: Classification and Complexity." Stichting Mathematisch Centrum, Amsterdam, Department of Operations Research, August 1980.

[4] Dempster, M.A., Lenstra, J.K., Rinnooy Kan, A.H.G., eds., Deterministic and Stochastic Scheduling. NATO Advanced Study Institutes Series. Series C: Mathematical and Physical Sciences, Vol. 84. D. Reidel, 1982.

[5] Gaspin, C., "Mission Scheduling." N89-26585.

[6] Graham, R.L., Lawler, E.L., Lenstra, J.K., Rinnooy Kan, A.H.G., "Optimization and Approximation in Deterministic Sequencing and Scheduling: A Survey." Ann. Discrete Math., Vol. 5, 1979, pp. 287-326.

[7] Hart, R.J., and Goehring, J., "An Application of Simulated Annealing to Scheduling Army Unit Training." U.S. Army Research Institute for the Behavioral and Social Sciences, Technical Report 727, October 1986.

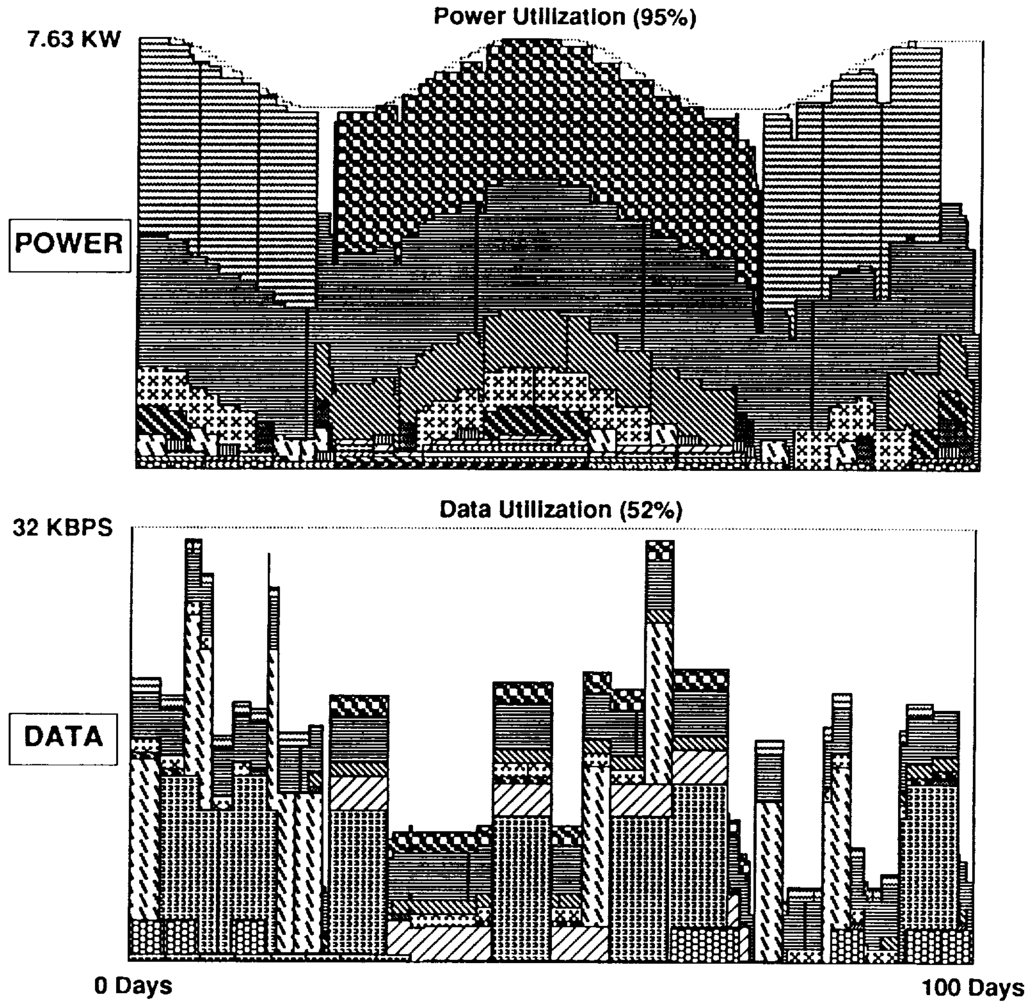
[8] Kurtzman, C.R., Benchmark Services for Space Station Program Support. White Paper, Space Industries International, Inc., July 1990.

[9] Kurtzman, C.R., "Experiment Scheduling for the Industrial Space Facility." AIAA-89-3138, AIAA Computers in Aerospace VII Conference, October 3-5, 1989.

[10] Kurtzman, C.R., Time and Resource Constrained Scheduling, with Applications to Space Station Planning. Ph.D. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts, February 1988.

[11] Kurtzman, C.R., and Akin, D.L., "The MFIVE Space Station Crew Activity Scheduler and Stowage Logistics Clerk." AIAA-89-3118, AIAA Computers in Aerospace VII Conference, October 3-5, 1989.

[12] Kurtzman, C.R., Akin, D.L., Kranzler, D., Erlanson, E., Study of Onboard Expert Systems to Augment Space Shuttle and Space Station Autonomy, final report of NASA Grant NAG5-445, July 31, 1986, NASA-CR-176958.



ID #	Experiment Name	Runs Scheduled	Max Runs Requested
4	Advanced Automated Directional Solid. Fur.	4	8
8	Chemical Vapor Transport - I	5	5
12	Diffusive Mixing of Organic Solutions	1	2
17	Electrodeposition	1	2
19	Electromagnetic Levitator	7	8
21	Float Zone Crystal Growth Facility	1	2
27	Gradient Furnace for the Get-Away-Special	8	8
34	Isothermal Dendritic Growth Experiment	7	8
41	Magnetic Isolation System	5	7
47	Monodisperse Latex Reactor System	8	8
49	Multiple Experiment Processing Facility	6	8
50	Non-Linear Optical Monomers	1	3
51	Non-Linear Optical Organic Crystals	1	3
52	Non-Linear Optical Thin Films	1	3
53	Normal Freezing Furnace	4	7
55	Organic Separations	2	2
58	Physical Vapor Transport of Organic Solids	8	8
59	Polymer Microstructure and Morphology	8	8
65	Space Ultra-Vacuum Research Facility	6	8
71	Reboost	1	1
72	Reboost	1	1
Total		86	110

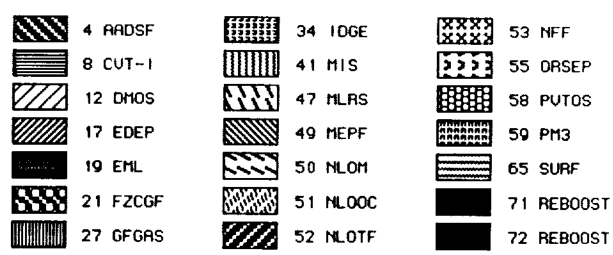


Figure 4: Optimized ISF Schedule

[13] Lawler, E.L., Lenstra, J.K., "Machine Scheduling with Precedence Constraints." Stichting Mathematisch Centrum, Amsterdam, Department of Operations Research, September 1981.

[14] Papadimitriou, C.H., Steiglitz, K., Combinatorial Optimization: Algorithms and Complexity. Prentiss-Hall, Inc., Englewood Cliffs, New Jersey, 1982.

[15] Patterson, J.H., "A Comparison of Exact Approaches for Solving the Multiple Constrained Resource, Project Scheduling Problem." Management Science, Vol. 30, No. 7, July 1984, pp. 854-867.

[16] Price, C.C., and Salama, M.A., "Scheduling of Precedence-Constrained Tasks on Multiprocessors." JPL Invention Report NPO-17219/6725, January 1989.

[17] Sponsler, J.L., "Genetic Algorithms Applied to the Scheduling of the Hubble Space Telescope." N89-26607.

[18] Waltbridge, C.T., "Genetic Algorithms." Technology Review, Vol. 92, No. 1, January 1989.

Appendix D--Bibliography

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Conference Introduction

CTA Incorporated, Planning & Scheduling Lessons Learned Study Executive Summary, June 29, 1990

Session 1. Concepts for Space Network Resource Allocation

Hornstein, R., J. Gardner, and J. Willoughby, Distributed Decision-Making for Space Operations: A Programmatic Perspective and A Technical Perspective on Tools and Techniques, AIAA/NASA Second International Symposium on Space Information Systems, Sept. 17, 1990

Information Sciences, Inc., Adaptations to the Traditional Practice of Systems Engineering Management Process: A Guidebook for Project Management, July, 1989

Goddard Space Flight Center, Customer Data Operations System (CDOS) Operations Management Service (COMS) Planning and Scheduling Concept Assessment, by Computer Sciences Corp., May 1990, DSTL-90-010

Wong, Y. and J. Rash, An RF Interference Mitigation Methodology with Potential Applications in Scheduling, Dec. 1990 (paper included in Appendix D)

Wike, J., Automatic Conflict Resolution Issues, Dec. 1990 (paper included in Appendix D)

Geoffroy, A., D. Britt and J. Gohring, The Role of AI Techniques in Scheduling Systems, 1990 Goddard Conference on Space Applications of Artificial Intelligence, May, 1990, NASA CP 3068

Durham, R., N. B. Reilly and J. B Springer, Resource Allocation Planning Helper - RALPH: Lessons Learned, 1990 Goddard Conference on Space Applications of Artificial Intelligence, May, 1990, NASA CP 3068

Session 2. SNC and User POCC Human-Computer Interface Concepts

Biefeld, E. and L. Cooper, Operations Mission Planner Final Report, March 15, 1990, JPL Publication 90-16

Goddard Space Flight Center, Design of Planning and Scheduling Interfaces: Guidelines and Display Concepts, by CTA, Inc., Dec. 1990, DSTL-90-027

Zoch, D., D. LaVallee, S. Weinstein and G. M. Tong, A Planning Language for Activity Scheduling, Dec. 1990, (paper included in Appendix D)

Goddard Space Flight Center,User's Guide for the Flexible Envelope Request Notation (FERN), by Computer Sciences Corp. and Loral AeroSys, Sept. 1989, DSTL-89-015

Weiland, W., E. Murphy, et al, Computer-Human Interaction Models (CHIMES)-2 System (Revised Report), GSFC Contract NAS-5-30680, Feb. 28, 1991

Thalman, N. and T. Sparn, SURE (Science User Resource Expert): A Science Planning and Scheduling Assistant for a Resource Based Environment, 1990 Goddard Conference on Space Applications of Artificial Intelligence, May, 1990, NASA CP 3068

Goddard Space Flight Center, Network Control Center (NCC) User Planning System (UPS) Detailed Design Specification, by Computer Sciences Corp., 1990

Session 3. Resource Allocation Tools, Technology, and Algorithms

Johnston, M., SPIKE: AI Scheduling for NASA's Hubble Space Telescope, Proceedings of the Sixth Conference on Artificial Intelligence, March 5-9, 1990, IEEE Computer Society Press, pp. 184-190

Kurtzman, C., Intelligent Perturbation Algorithm for Space Scheduling Optimization, Dec. 1990 (paper included in Appendix D)

Goddard Space Flight Center, A Study of Optimization Techniques for Activity Scheduling, by Computer Sciences Corp., Oct. 1989, DSTL-89-D11

Logan, J. and M. Pulvermacher, Range Scheduling Aid User's Guide, Jan. 1990, WP-6965, MITRE Corp. Bedford, MA

Goddard Space Flight Center, Request-Oriented Scheduling Engine (ROSE) Concepts and Capabilities, by G. Tong, July 1990, DSTL-89-020

Britt, D., A. Geoffroy and J. Gohring, Managing Temporal Relations, 1990 Goddard Conference on Space Applications of Artificial Intelligence, May, 1990, NASA CP 3068

McDonnell Douglas Space Systems Co., COMPASS 1.4, 1989, COMPASS Information Planning and Scheduling Group, Houston, TX

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16. Abstract

This report describes the results of the Space Network Control (SNC) Conference on Resource Allocation Concepts and Approaches, which was held at the Goddard Space Flight Center on December 12-13, 1990. In the late 1990s, when the Advanced Tracking and Data Relay Satellite System is operational, Space Network communicatyion services will be supported and controlled by the SNC. The goals of the conference were to survey existing resource allocation concepts and approaches, to identify solutions applicable to the Space Network, and to identify fruitful avenues of investigation in support of the SNC development. About 75 people took part in the conference, both as speakers and as participants in working-group discussions, to elicit recommendations for the future SNC. The conference was divided into three sessions; 1) Concepts for Space Network Resource Allocation, 2) SNC and User Payload Operations Control Center (POCC) Human-Computer Interface Concepts, and 3) Resource Allocation Tools, Technology, and Algorithms. Key recommendations addressed approaches to achieving higher levels of automation in the scheduling process. Prototyping was mentioned as an effective mechanism for verifying operations concepts and evaluating specific technology risks.

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