Planning and Scheduling of Earth Observing Satellites

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Abstract—The roles and interactions of activity planning and scheduling for Earth Observing Satellites are based on factors such as mission objective, system assets and resources, system and spacecraft constraints, planning criteria, scheduling strategies, timelines, and desired level of automation and operator interaction.

Activities are generalized into four categories: accomplish the mission objective, support the mission objective, manage the system resources, and maintain the system assets.

This paper discusses factors that influence the planning and scheduling design and design complexities. Included is how the design addresses modeling of the spacecraft subsystems and states when incorporating spacecraft capabilities, constraints and operating guidelines. [1, 2]

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1. INTRODUCTION

Planning consists of placing activities on a timeline, assigning assets, and allocating resources to activities based on planning criteria and constraints. Scheduling consists of defining the detailed spacecraft operations that make up the activities, based on mission requirements, scheduling strategies, and constraints. The schedule must be free of constraint violations and have the detail needed for translation into commands and data for uplinking to the spacecraft. Scheduling incorporates models of the spacecraft subsystems and states involved in each activity. These models are used in developing the activity operations and in checking constraints.

2. PLANNING

Figure 1 illustrates the Planning timeline and Figure 2 presents the Planner design factors discussed in this section.

Role of Planning

The plan provides insight into mission data collection opportunities and the ability to accommodate particular collection needs. It serves to coordinate collection activities across systems of spacecraft or individual spacecraft or collection windows, for the optimization of collection and spacecraft utilization. An out-day plan provides estimate of the collection windows, asset assignment and resource allocations as it matures to Day 1. Day 1 of the plan provides the final collection windows, asset assignment and resource assignment.

A plan is definitely needed. It is used to coordinate human activity and facility/equipment usage. It provides a focus for negotiating space-ground communication, if provided external to the collection system.

Most spacecraft planning covers a 7-day period. A common question is why 7 days; why not 24 hours? The 7-day plan is primarily driven by the need to plan personnel for equipment maintenance, especially for off-day-shift maintenance. While a multi-day plan is needed, it can be less than 7 days, but a 24-hour plan is definitely not practical from an operations coordination and staffing perspective.

The next question is why generate a 24-hour or longer plan of high level activities, instead of a schedule of detailed operations. In other words, since you must have a scheduling capability, why not use that capability to generate a plan? This is a valid trade space to explore, but generally planning capabilities cannot be met by scheduling functionality because:

- It is likely to take a long time, cpu-time-wise, to generate a schedule covering a long time period. A scheduler that works across spacecraft and systems would have to be simplified to achieve acceptable run-time.

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[2] IEEEAC paper #1155, Version 3, Updated December 26, 2006.

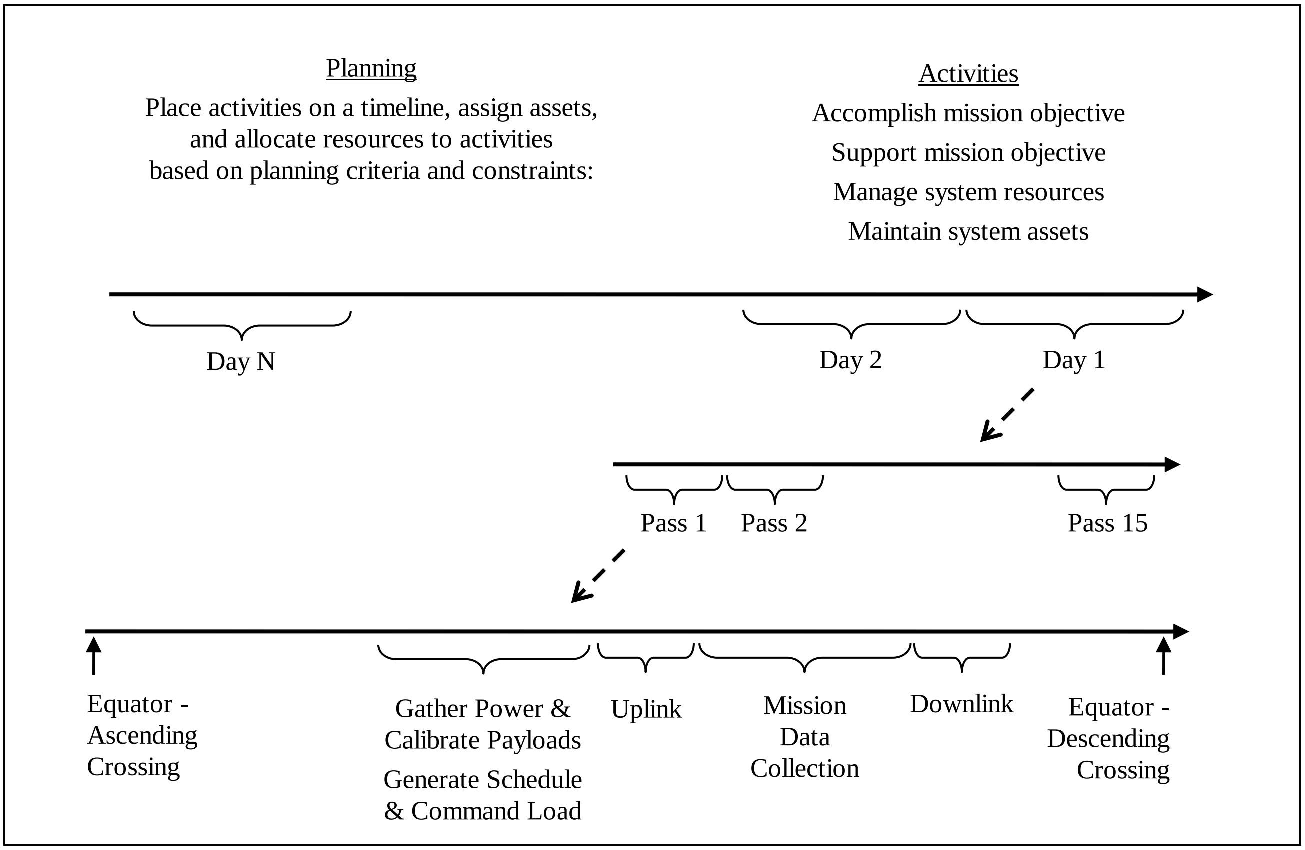

Figure 1. Planning Timeline

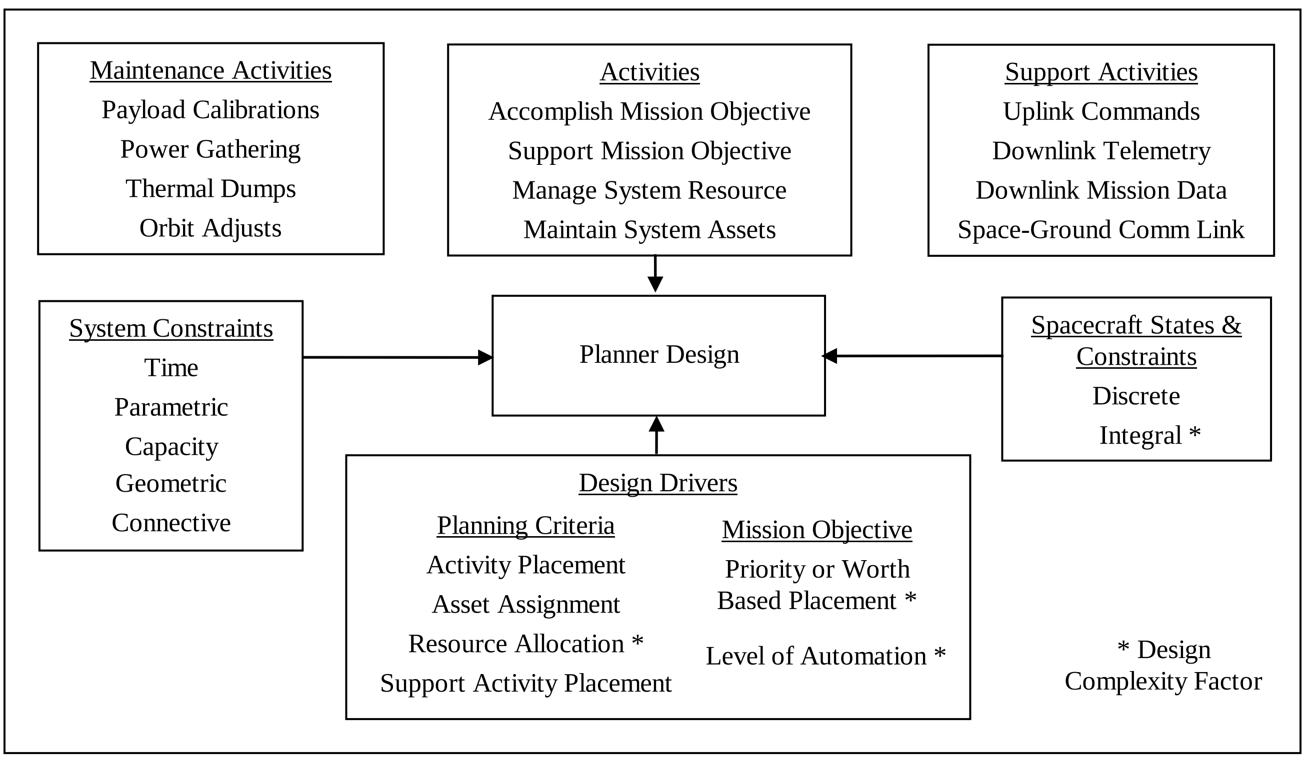

Figure 2. Planner Design Factors

- The scheduling functionality is likely to be overly complicated, particularly when dealing with systems of collection spacecraft versus dealing with only one spacecraft.

- It can be difficult to reliably calculate/propagate the spacecraft state, e.g. position, power, momentum, and thermal, over 24 hours and nearly impossible over a 7 day time span.

Assets and Resources

Activities require system assets and resources. A system asset is a physical entity. Examples of assets are: a mission spacecraft, a spacecraft payload, a communication spacecraft, and a ground command/receive station. Examples of payloads are mission sensors and communication antennae.

A resource is a system asset that is needed to support an activity but is in short supply, e.g. a relay spacecraft. A resource is also a quantity of something that is consumed or replenished by an activity, e.g. power or memory.

Activities

Activities are generalized into four categories: accomplish the mission objective, support the mission objective, manage the system resources, and maintain the system assets.

Examples of support activities are: uplink spacecraft commands and loads, downlink spacecraft telemetry and mission data, and provide ground to spacecraft communications.

Examples of maintenance activities are: payload calibrations and alignments and spacecraft power and thermal maintenance.

Planning Criteria

Activities are placed on a timeline according to planning criteria, while observing system constraints so as to maximize the accomplishment of the mission objective.

Planning criteria govern the placement of activities, the assignment of assets, and the allocation of resources. The planning criteria also specify what supporting activities are required by the mission activity. Planning criteria are rules and methods that are implemented through a combination of code, database, and operator interaction.

There is not a lot of latitude in the placement of a mission objective activity. It is placed at a point in time that satisfies the mission collection requirements such as viewing geometry and mission data quality. If there are several possibilities for activity placement, then the planning criteria can specify the best placement. If the best placement of the activity is in conflict with the placement of another activity, then the planning criteria can resolve that conflict.

Planning criteria can be used to place supporting activities that are essential to a mission activity. For example, once a mission activity has been placed on the plan, the planning criteria could specify the placement of a schedule uplink activity immediately prior to the mission activity. The planning criteria could specify the placement of a mission data downlink activity coincident with the mission activity, if the data is to be collected and downlinked in real-time. Or the planning criteria could specify the placement of a mission data downlink activity after the mission activity, if the mission data is collected and stored while the spacecraft is out of contact with the ground receive facility.

Planning criteria are also used to place maintenance activities. Some activities require geometries that can be achieved at only one part of the orbit. For example some payload calibrations require specific Sun-to-spacecraft or star-to-spacecraft geometries. Also, some calibrations require collection of all the calibration data. Other activities, such as power gathering and thermal dumps, are more flexible in their placement since their geometries can be achieved at numerous times during an orbit. Power gathering requires pointing the solar panels toward the Sun and thermal dumps require pointing the thermal radiator toward deep space.

Calibration and power gathering activities can also be considered as support activities rather than maintenance activities, when their placement on the plan is governed by the placement of the mission activity. That is, it could be necessary to calibrate a payload or to gather power to fully charge the spacecraft batteries immediately prior to the mission activity.

The Planner places the mission activities on the timeline according to activity priority or worth. That is, the mission activity priority or worth is used to resolve conflicts between activities when placing them on a plan. Priority or worth is also used to assess the value of a plan or of competing candidate plans.

For example, mission activities are said to be in conflict when placing them on a plan when there are not enough resources to support all of the mission activities. Spacecraft power is classified as a resource when the spacecraft does not have enough power capacity to support all the opportunities for mission data collection across a day of operations. One approach is to express power capacity as a duty-cycle constraint, that is, the number of minutes of mission data collection allowed over one pass, over two consecutive passes, and continuing on to over fifteen consecutive passes. Then the Planner uses activity priority or worth to determine which activities are, or are not, placed on the plan when placement will result in a violation of the duty-cycle constraint.

The design of methods that incorporate priority or worth needs to accommodate the following observations. A few high priority or worth objectives among lots of lower priority or worth objectives can make it difficult to select a best plan. Since all the candidate plans have high priority or worth objectives, the lower priority or worth objectives are just noise to the right of the decimal place.

There is a subtle difference between allocation and assignment. Assignment is a mapping of activities to one of a few discrete assets. Allocation involves the distribution of a resource, such as power, across a number of activities. Allocation of a resource in short supply can require a complex set of rules and methods for determining the best combination of mission activity placement and asset or resource usage.

System Constraints

Constraints can be classified as time, parametric, capacity, geometric, and connective and are defined below:

- A time constraint defines the relationship of one activity to another activity or to a defined point in time or in orbit. Time constraints can be prohibitive or inclusive.
- A constraint being parametric means that the parameter must stay above or below a particular value.
- A capacity constraint defines the number of allowed occurrences of a particular activity over an interval of time.
- A geometric constraint specifies specific geometry related to the spacecraft, payload or space-ground communication.
- A connectivity constraint defines the existence of several activities at the same time, such as a space-ground communication link and mission data collection for real-time downlink.

Spacecraft States and Constraints – Discrete and Integral

The modeling of spacecraft states can be categorized as discrete or integral. Spacecraft equipment being on or off is an example of a discrete state. Spacecraft battery power is a state that requires integral modeling. You must start with a known state and then model power debit and credit.

Spacecraft constraints can be categorized as discrete or integral. An example of a discrete constraint is not pointing an optical sensor directly at the sun. An example of an integral constraint is not pointing an optical sensor to within ten degrees of the sun for more than five minutes within any forty minute period.

Of course a spacecraft state that requires integral modeling can also be associated with a discrete constraint. An example is the temperature on a piece of equipment not exceeding a maximum level.

Activity Selection Order and Constraint Checking

Planners select activities from a pool of activities and place them on a timeline in a manner that satisfies all constraints and requirements. Activities can be selected in time-order or in non-time-order, based on the algorithmic technique employed. A non-time-ordered selection requires a total re-integration of the sequence when an activity is added and an integral constraint is checked or when a spacecraft state calculation requires an integral model. A time-ordered selection allows the integration to occur incrementally as the plan is developed.

Activity selection based on activity priority results in a non-time-order selection. This coupled with integral constraints may require a more complex Planner design. Checking integral constraints each time an activity is added will impact Planner run-time. If run-time is an issue, then the integral constraints will have to be checked after the candidate plan is built. This, in turn, will require additional logic to resolve any constraint violations.

Activity selection based on worth can be carried out in the time-order which facilitates the checking of an integral constraint. But this adds complexity to the Planner design for the construction candidate plans and for the selection of the high-worth plan.

Planning Categorization

Planning paradigms can be generalized into categories based on how the mission objective, assets, resources, and constraints drive the planning criteria. The generalization is based on how the mission activity is generated and placed, how the support activities are generated and placed, and how the resources are to be allocated.

Mission activities can be classified as: fixed, floating, flexible, and floating-flexible:

- A fixed activity is of specified duration and placed at a specified time.
- A floating activity is of specified duration and placed anywhere within a specified time interval.
- A flexible activity can have its start and stop time trimmed if necessary to resolve a conflict, constraint, or allocation.
- A floating-flexible activity can be planned anywhere within a specified time interval and can have its start and stop times trimmed, if necessary.

First Categorization

The placement of the mission activity is governed primarily by the availability of assets. The mission and support activities can be generated and placed without needing to accommodate a consumable resource or to allocate a replenishable resource.

The mission activity is placed within specified timelines, i.e. fixed, floating, or flexible activity. Then the associated support activities are added. Activity priority or worth is used to resolve activity conflicts or constraint violations.

Second Categorization

The placement of the mission activity is governed primarily by the availability of consumable/replenishable resources. This results in a more complex Planner design.

A mission activity is placed so that it has the most worth, i.e. floating-flexible activity and then the support activities are added to the plan, including those that provide or replenish resources that are consumed by the mission activity, e.g. gather power or dump the data buffer. The support activities must be defined to provide the proper quantity of resources. Finally, mission activities are modified as necessary to accommodate the amount of resources available.

Conversely, it is easier to deal with environments where a resource can be fully replenished before the next mission activity or where all activities are somewhat equal in importance with no need to save a portion of a resource for later consumption.

An additional complexity is dealing with resources that must be smartly allocated. That is, a resource should not be consumed by a low priority or worth activity to the extent that a high priority or worth activity cannot be accomplished.

This may involve sophisticated optimization strategies based on the operations research branch of mathematics. While this paper does not discuss the various kinds of operations research techniques, the more critical the mission and the more constrained the activities, the more sophisticated the techniques need to be.

Level of Automation

Operating a spacecraft may require a high level of Planner automation with an operator role of mostly review and approval, rather than being integral to placing activities on the timeline and resolving activity conflicts, constraint violations and resource allocations. The level of required automation is determined, in part, by the mission collection activity loading, dynamics, and timeline.

The operator can take an active role in Planning when the pool of activities is relatively stable and the number of activities is not excessive. However, when the pool of activities is in flux due to adding new activities, removing accomplished activities, or modifying existing activities, a higher level of automation will be needed to avoid operator overload.

Some missions require Planning to be completed by an established time of day so that Scheduling for the first pass of the day can commence. These missions may also require Planning to incorporate the most recent change mission activities, thus establishing a Planning start time. There is a design trade in the level of automation, and thus design complexity, needed to meet the Planning start and end times versus the currency of mission activities.

There is also design trade relative to the cost of operators versus the cost of including a high level of automation in the design. The operator cost can be quite significant for long term missions.

3. SCHEDULING

Figure 3 illustrates the Scheduling timeline and Figure 4 presents the Scheduler design factors discussed in this section.

Planning and Scheduling for a spacecraft with a primary mission activity of ground imaging starts with a database of targets and collection requirements.

Planning defines the mission collection windows. These are the periods of time when the spacecraft is passing nearby targets that can be collected in a manner that satisfies the target's collection requirements.

A schedule is a time ordered series of spacecraft activities and activity transitions. The transition allows for a change of spacecraft attitude and configuration from one activity to another.

The schedule must be free of constraint violations and have the detail needed for translation into commands and data for uplinking to the spacecraft. These constraints are fully documented in spacecraft and ground specifications.

Scheduling inputs include states of the spacecraft, mission objective, and environment. The mission objective state includes the latest mission tasking and mission accomplishment. For an Earth observation mission with an optical payload, cloud cover is part of the environmental state. Spacecraft state includes its updated position knowledge, battery charge, and temperature of key components.

Scheduling selects targets and places them on a timeline within the collection window so as to meet the mission objective while also satisfying collection requirements, scheduling strategies, spacecraft constraints, and spacecraft operating guidelines.

The Scheduler defines the spacecraft collection operations including the collection start and stop times and parameters defining the spacecraft orientation and sensor configuration. It also allocates sufficient time between collection operations for spacecraft reconfiguration and reorientation.

Mission Objective

The Scheduler objective is usually based on the worth or priority of the targets. A worth-based scheduler places the collection activities on a schedule to maximize the total worth of the schedule. A worth-based scheduler evaluates many candidate schedules in the process of discovering the best schedule.

A priority-based scheduler is founded on the principle that a single target of given priority is more valuable than any number of other lower priority targets. The scheduler places collection activities on a schedule in order of target priority. The scheduler has logic for selecting between targets of equal priority. The priority-based scheduler considers only one schedule, not several schedules.

Target Collection Requirements

Collection requirements specify the conditions under which the targets are to be imaged. Collection requirement categories include image quality and geometric constraints.

The image quality collection requirement is usually the maximum acceptable ground resolution. A ground resolution of one meter means two objects one meter apart appear as separate objects in an image. A maximum acceptable ground resolution of one meter means an image with a ground resolution greater than one meter is not acceptable.

The line of sight from the spacecraft to the target is called the look vector. Geometric collection requirements can be the minimum and maximum look elevation angle as well as the minimum and maximum look azimuth angles, all measured at the target.

Another geometric collection requirement for optical images can be the minimum and/or maximum Sun elevation angle measured relative to the target location.

Scheduling Strategies

The Scheduling timeline is constrained by several factors as illustrated in Figure 3. The timeline must complete in time to allow translation and uplink at the next uplink opportunity. The start time is determined by run-time and desired currency. Currency is a measure of how up-to-date the inputs are relative to the changing mission objective, spacecraft, and environmental states.

There can be mission scenarios that require Scheduling to incorporate the most recent changes to the mission objective state, which includes the latest mission tasking and mission accomplishment. The higher the level of desired currency, the shorter the Scheduler run-time must be.

There can also be scenarios where there are many more targets to collect than time to collect. An analysis should be conducted to determine if the ground modeling of spacecraft capabilities and constraints is limiting collection performance. That is, does the ground modeling providing a too-conservative estimate of spacecraft capability. Modeling of spacecraft power is often a limiting factor. For agile spacecraft, modeling of spacecraft slew and scan capabilities will also be limiting factors.

Efficient collection covers the target in minimum time. For a spacecraft with an optical payload, the closer the spacecraft is to the target, the better the ground resolution and the smaller the field of view. But the smaller field of view may mean that more operations are needed to cover the target. Therefore, getting better-than-required ground resolution may result in additional coverage operations and thus, less efficient coverage.

Figure 5 illustrates that there can be a design trade of increased collection versus improving currency. The trade is needed when increasing collection requires a higher performance scheduler algorithm and higher fidelity models which in turn increases run-time and, correspondingly, degrades currency.

Cost may also be part of the design trade. The run-time can be decreased by using a faster, and likely more expensive, compute server. The higher performance scheduler and higher fidelity models may have an increased cost to develop and implement.

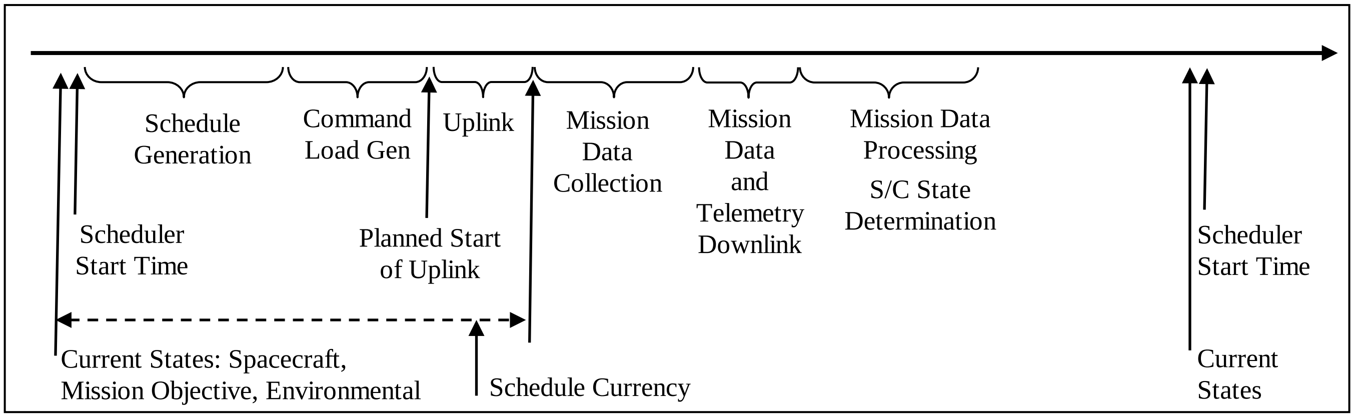

Figure 3. Scheduling Timeline

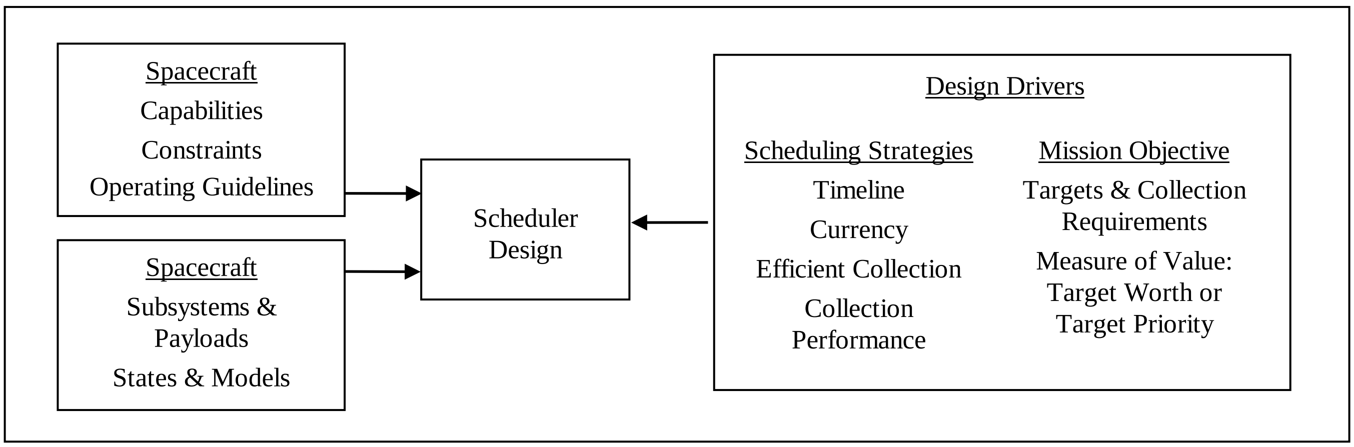

Figure 4. Scheduler Design Factors

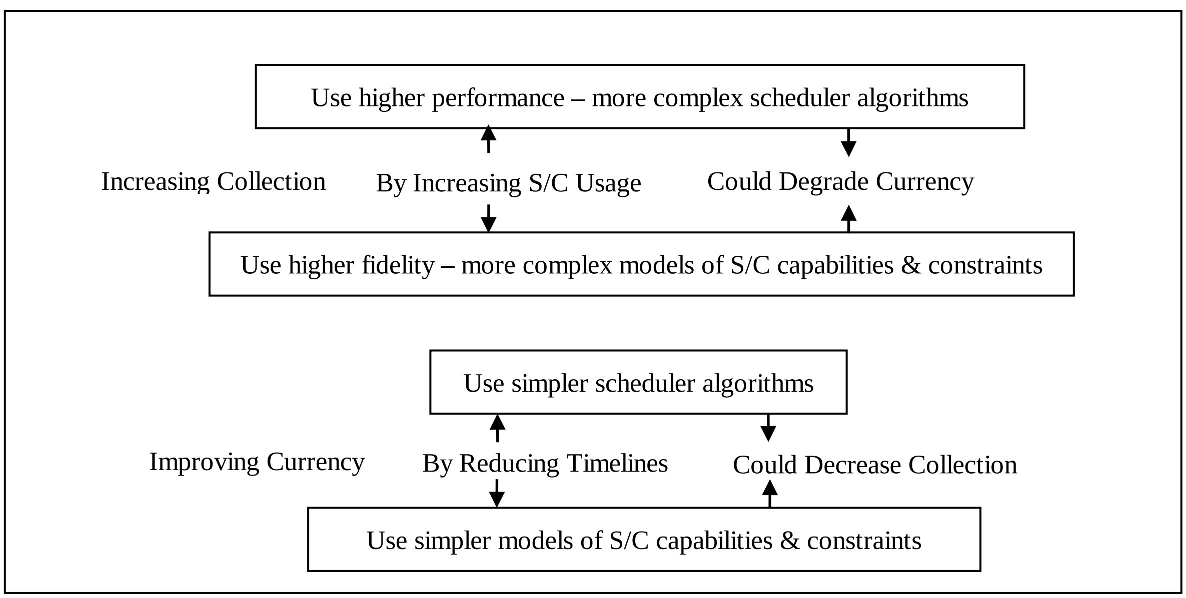

Figure 5. Design Trade of Increasing Collection versus Improving Currency

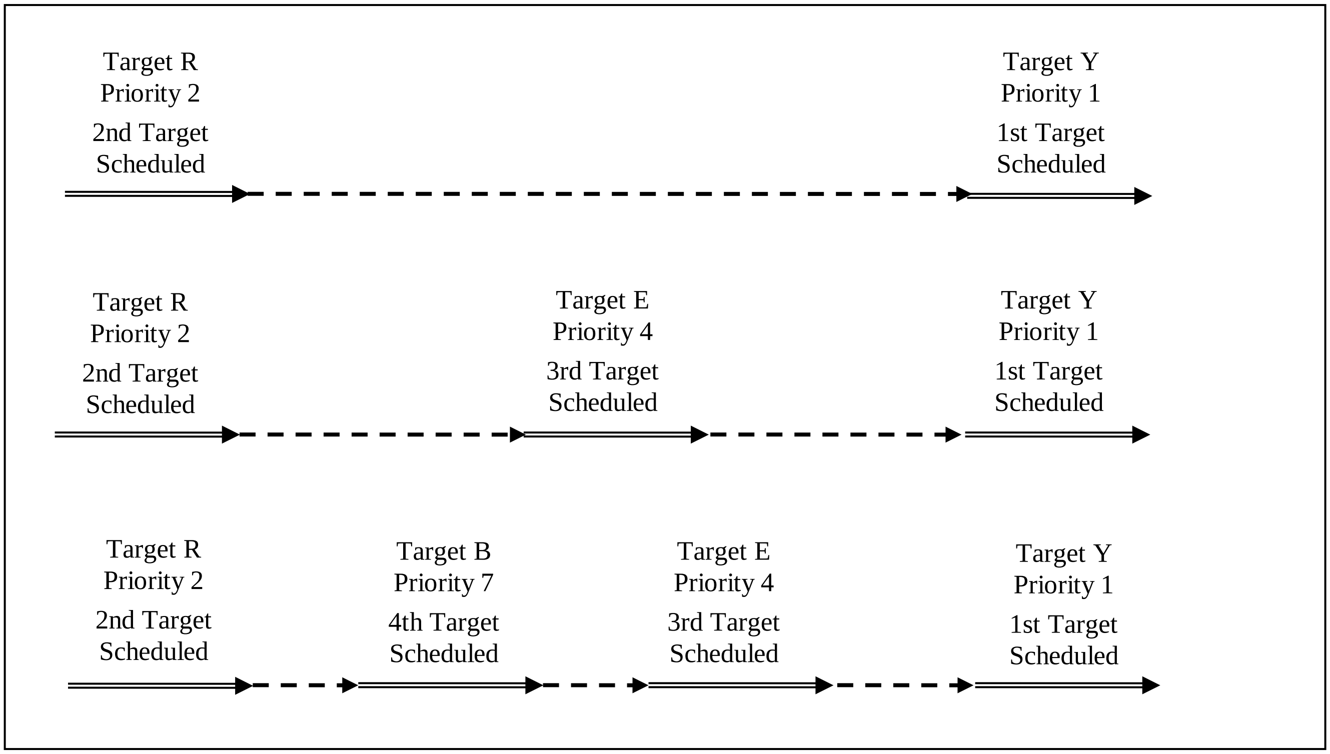

Figure 6. Non-Time Ordered Scheduling

Integral Constraints and Integral States

The Scheduler design becomes more complex when scheduling targets in non-time order and dealing with integral constraints and integral states. Figure 6 illustrates scheduling targets based on the highest priority. Target Y, with priority 1, is scheduled first and target R, with priority 2, is scheduled second, resulting in a schedule with a scan of target R followed by a slew to and a scan of target Y.

Next, target E, with priority 4, is scheduled between targets R and Y. The slew between targets R and Y is replaced by a slew to, and scan of, target E, followed by a slew to target Y. Then target R, with priority 7 is scheduled between targets R and E, forcing target E to be scheduled later in time. This forces a recalculation of all the slews and scans between targets R and Y.

Thus each time targets are added between existing targets, the recalculation of the slew and scan results in a re-check of integral constraints and re-calculation of integral states.

4. CONSTELLATION PLANNING AND SCHEDULING

Figure 7 illustrates one approach to Planning and Scheduling for a constellation of spacecraft. The Constellation Planner constructs an integrated plan covering all the spacecraft, allocating shared resources across the spacecraft.

An example of shared resources is ground command/receive stations. The uplink and downlink activities supporting the mission data collection activities may be limited by the availability of the ground command/receive stations. This, in turn, limits the extent and placement of the mission data collection activities.

The individual plan for each spacecraft is extracted from the integrated plan and then provided to the individual Schedulers. The schedules are constructed, one at a time, for each spacecraft and each spacecraft pass. The mission accomplishment from each spacecraft mission data collection activity is fed back into the collection data base. The targets that were scheduled, but not successfully collected, remain available for collection by another spacecraft.

Figure 8 illustrates another approach to Planning and Scheduling for a constellation of spacecraft. In this case, a Constellation Scheduler simultaneously schedules all the spacecraft. The advantage of this approach over scheduling one spacecraft, one pass at a time, is that collection can be optimized across the spacecraft. The disadvantage is that the feedback of mission accomplishment into the collection database takes place after the schedules have been constructed.

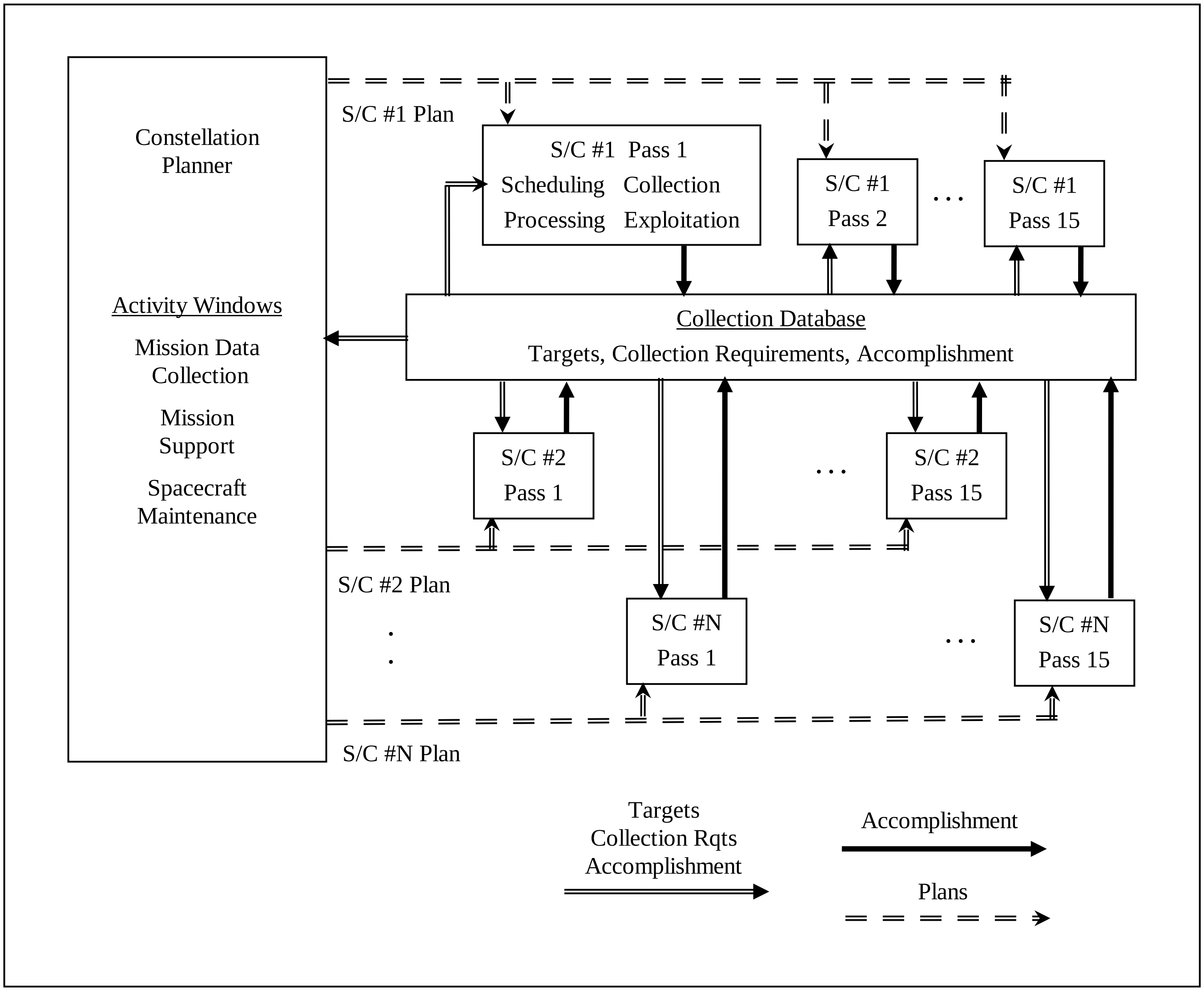

Figure 7. Constellation Planner and Individual Spacecraft Schedulers

5. SPACECRAFT CAPABILITIES AND RESTRICTIONS

The spacecraft specification contains requirements covering the operation of spacecraft subsystems, payloads, and equipment in support of executing the spacecraft mission, as well as the maintenance of the spacecraft health and safety.

The ground specification contains the requirements covering ground operations, which includes requirements in support of spacecraft operations.

The space-ground interface control document contains the spacecraft requirements and the ground requirements in support of data flow between the spacecraft and the ground. This includes data definitions, formats, ranges, quantity, and timelines.

Spacecraft Capability, Subsystem, and Payload

The spacecraft consists of its subsystems, including mission data collection, power generation and distribution, thermal control, attitude control, command, telemetry, communication, propulsion, and structure.

A subsystem consists of payloads, equipment, hardware, firmware, and software. The subsystem is configured to provide a spacecraft capability.

Spacecraft State

The spacecraft state is a collection of parameters that cover all relevant spacecraft conditions: dynamics, subsystems, payloads, and equipment.

Dynamic states include orbital position and velocity, attitude (body coordinate frame unit vectors), and body rotational rate.

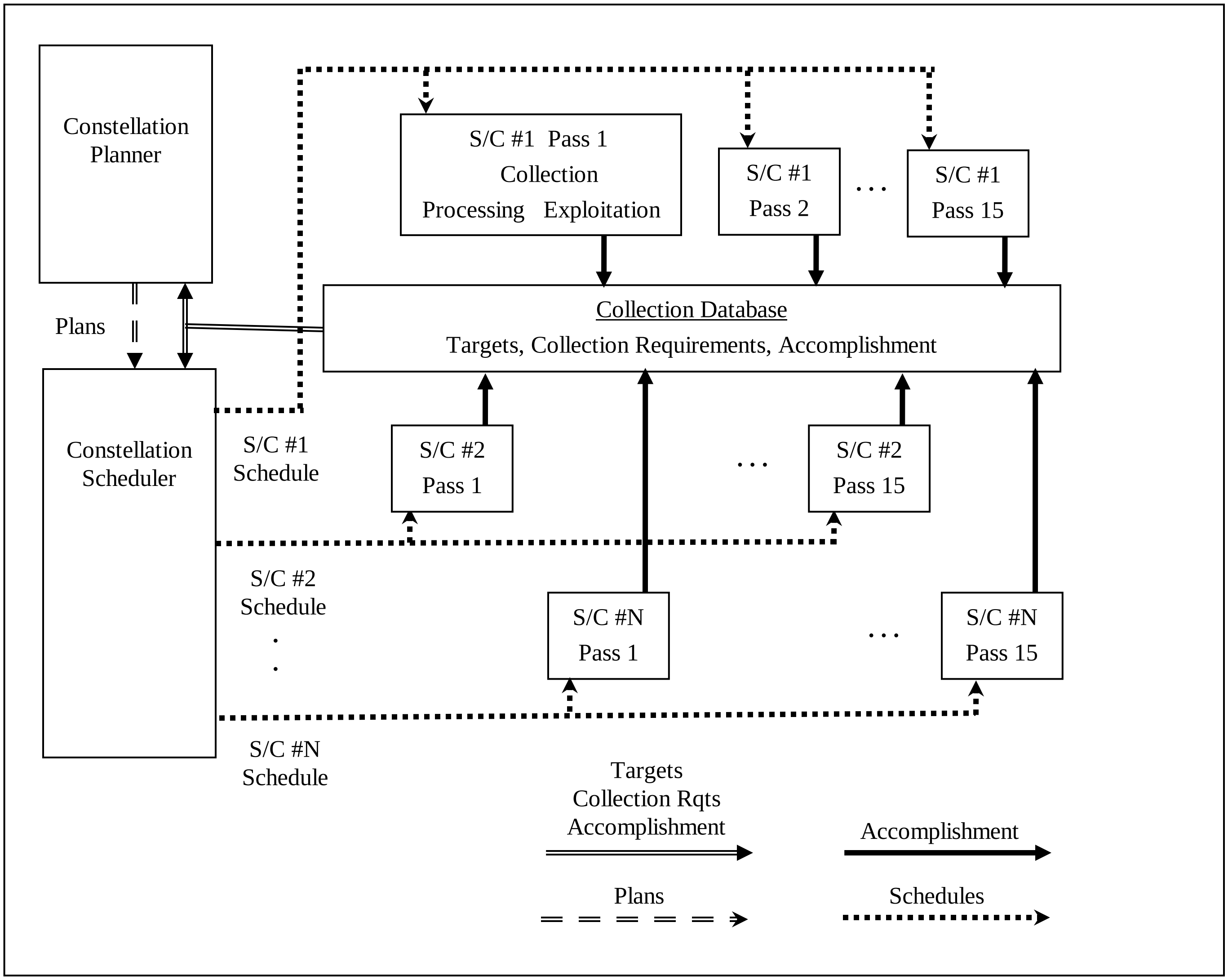

Figure 8. Constellation Planner and Constellation Scheduler

The power state consists of payload and equipment power usage, level of solar power, and battery state of charge. The thermal state includes payload and equipment temperature levels.

A subsystem state is its configuration, i.e. the set of parameters used to control the subsystem. This configuration determines the level of capability provided. For example, imaging subsystems may have configuration parameters that control the ground resolution. Space to ground communication subsystems have configuration parameters that control the output power of the transponders.

The values of the spacecraft state parameters are either determined on board the spacecraft and downlinked as telemetry or determined by ground processing, based on telemetry from the spacecraft.

Spacecraft Restrictions

A spacecraft is operated in a manner that complies with the restrictions called out in the spacecraft specification. These restrictions cover spacecraft command sequences, telemetry limits, constraints, and operating guidelines.

Command sequence checks are carried out prior to uplinking and telemetry limits checks are carried out on board. Spacecraft constraints and operating guidelines are enforced by the ground Scheduler.

Spacecraft constraints can be classified as hazardous or non-hazardous. Violating a hazardous constraint can result in immediate or near-term degradation or damage. The spacecraft specification provides descriptions of each constraint and its correspondingly acceptable value, as well as actions to be taken by the spacecraft if the constraint is violated.

Actions can include no action, advance to the next activity, or a system reconfiguration into a safe mode of operations. A safe mode of operations is when the spacecraft is gathering power, preparing to establish a communication link with the ground, and awaiting commands, while otherwise operating in a very benign state with no mission execution. Generally the spacecraft cannot resolve or mitigate a constraint violation and then continue with the current activity.

Spacecraft guidelines are generally associated with operating the spacecraft in a manner that supports mission data quality, spacecraft state of health, and spacecraft design life.

Guidelines specifying frequency and types of calibrations and alignments of the mission data collection subsystem are used to maintain the quality of the mission data. Two examples of guidelines for maintaining a satisfactory thermal state are limiting equipment on-time and requiring periods of thermal dump.

6. MODELING OF SPACECRAFT ACTIVITIES

The ground has the responsibility of assuring that the spacecraft mission activities, the mission support activities, and the spacecraft transition to and from each activity are free of constraint violations.

Scheduling models spacecraft activities and transitions and checks them for constraint violations. If a constraint violation is discovered, it must be resolved in order to produce a usable schedule. A reactive strategy is to take action when a constraint is violated while constructing and adding activities on the schedule. A proactive strategy is to take action to avoid a constraint violation by scheduling activities well away from a violation.

Model Accuracy

The model of a spacecraft subsystem or state, as implemented in scheduling, may be only an approximation of the model provided in the spacecraft specification.

Inputs to the ground model are, themselves, based on models. For example, the scheduler can only estimate the spacecraft position and velocity at a future point in time. The farther out in time, the greater the uncertainty. This uncertainty arises in part because of the uncertainty in atmospheric drag and its effects on the spacecraft.

The model provided in the spacecraft specification may be too complex to be implemented in scheduling while also meeting the timeline. A simpler, more conservative model, and thus less accurate, may be needed by scheduling. Therefore another trade that arises is level of schedule currency versus maximizing vehicle capabilities. Refer to Figure 5 and its previous discussion.

Additionally, the model in the spacecraft specification may be only an approximation of the actual spacecraft operations since the spacecraft subsystem or state may be too complicated to model accurately. For an example, refer to the discussion of the thermal state below.

Any ground approximation in the ground model should be on the conservative side. At the same time, for scheduling scenarios with scheduling strategies that drive a spacecraft toward its maximum capabilities, the ground model should not be too conservative.

If the ground model is used to check a hazardous constraint, then it is important for the model to be conservative to reduce the likelihood of the spacecraft detecting a constraint violation, interrupting the schedule execution, and going into a safe mode of operations.

Model Validation

For a spacecraft that is under development, the model in the spacecraft specification is initially validated against spacecraft engineering models. For a spacecraft that is on-orbit, the model is validated against actual operations.

The model implemented in scheduling goes through a validation, verification, and calibration process. The ground model is validated against the spacecraft specification model. The implementation of the ground model is then verified.

The ground model may also undergo periodic calibration by comparing the model results with actual state values as determined from down-linked telemetry.

The ground model parameters should be database-defined to allow for adjustments arising from model calibrations, as well as spacecraft degradation and anomalies.

If the ground model implemented in scheduling is at risk of being inaccurate and not always conservative, a final constraint check with a more accurate model may be needed. A final constraint check may also be needed if dealing with integral constraints, states, and scheduling in a non-time-order manner.

Constraint Model Versus Constraint Guidelines

There are two approaches to satisfying a spacecraft constraint. The first is to implement a model in scheduling. The second is to schedule according to guidelines. However the guidelines, themselves, must be validated against a robust set of scenarios. The two approaches are illustrated by the discussion of a thermal state.

The first approach is to have a thermal model of the spacecraft that predicts temperatures for each component with a temperature constraint. Components that do not have temperature constraints but are part of the thermal environment are also included in the thermal model.

The model accommodates, for example, thermal interaction of the spacecraft structure, equipment, heat pipes and radiators, orientation of the spacecraft relative to the Sun for direct exposure and shading, equipment operating times, and thermal dumps.

The model is used to predict the thermal state and compare it to constraint limits, either during formation of the schedule or afterwards, as a final constraint check prior to uplinking the schedule command load to the spacecraft.

If the model flags a constraint violation during schedule formation, then a strategy is enacted to resolve the constraint violation. The easiest reactive strategy is to insert a thermal dump, but that results in a loss of opportunity to collect mission data. A more complex reactive strategy is to insert a thermal dump at an earlier point in the schedule where it would have less mission impact. A proactive strategy creates mission activities that have favorable thermal characteristics.

The second approach is to schedule according to constraint guidelines that assure that the thermal state will remain within acceptable limits. For example, the guidelines would limit equipment on-time, limit the periods of time the thermal radiators are pointed in the direction of the Sun, and require periods of thermal dumps.

7. CONCLUSION

Planning consists of placing activities on a timeline, assigning assets, and allocating resources to activities – all based on planning criteria and constraints.

Scheduling consists of defining the spacecraft operations that make up the activities based on mission requirements, scheduling strategies, and constraints.

The level of design complexity depends, in part, on several key factors.

The design is less complex when the placement of the mission activity is governed primarily by the availability of assets. This is true when the mission and support activities can be generated and placed without needing to accommodate a consumable resource or allocate a replenishable resource.

The design is more complex when the placement of the mission activity is governed primarily by the availability of consumable and replenishable resources.

The design is more complex when the activities are placed on a plan or schedule in non-time-order because this requires a total re-integration of the sequence when an activity is added, when an integral constraint is checked, or when a spacecraft state calculation requires an integral model.

The design is less complex when activities are placed on a plan or schedule in time-order. This allows the integral constraints or integral states to be handled incrementally, as the selection proceeds.

The design is more complex when scheduling is required to utilize the maximum capabilities of the spacecraft because this could require the use of more complex models of spacecraft constraints and states.

The cost-effective Planner and Scheduler design is achieved by carrying out trades of design complexity and level of automation versus mission objectives.

REFERENCES

D. Kaslow and J. Shupp, "Activity Planning" in *Cost-Effective Space Mission Operations*, Larson, Boden and Squib, Ed. New York: McGraw-Hill, 2006.

BIOGRAPHY

Dave Kaslow has thirty-three years of experience at Lockheed Martin in both the technical and management aspects of developing a ground mission element.

He is also editor of Spacecraft Digest at www.stk.com, which tracks current and future spacecraft and spacecraft missions.

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