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Observing Solar System Objects with JWST

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Abstract

This document reports the results of a study to estimate the cost to the Science and Operations Center (S&OC) for supporting observations of Solar System objects with the James Webb Space Telescope (JWST). To facilitate this investigation, a moving target operations concept was adopted and its requirements were identified. The cost to implement these requirements has been estimated. To minimize the cost of a JWST Solar System observing program, maximum reuse of the moving targets capabilities from the HST ground system has been assumed. While this operations concept supports observations of any Solar System body within JWST's field of regard, the limitations of the flight hardware will ultimately determine which objects can be observed. We recognized that observations of some Solar System bodies will need to occur within highly constrained windows of time to observe specific events. The architecture of the JWST event driven scheduling system has the flexibility to support such observations, although a loss of observatory efficiency, which we estimate will be very small, may result. The cost to the S&OC for supporting observations of moving targets, which includes software development, maintenance, integration and testing, and one year of operations is estimated to be $2.73M. Afterwards, when all development and regression testing is completed, the cost for maintenance and operations is estimated to be $254K/year. The development phase represents an increase of 5% over the costs to the S&OC for observations of fixed targets. The operations phase represents an increase in cost of 3%. The total cost to enable observations of moving targets can be estimated only after other elements of the JWST project undertake a similar study.

Observing Solar System Objects with JWST

I. Introduction

The James Webb Space Telescope (JWST) will be an infrared optimized telescope observing the Universe from the Earth-Sun L2 point. Although the primary science driver for this observatory is the study of distant targets with fixed positions on the sky, it could also carry out important observations of Solar System objects. The legacy of HST's success in exploring the Solar System, and the high level of public interest in the discoveries that followed, is motivation to consider observations of Solar System objects with JWST. With the architecture of the observatory and the ground system sufficiently well defined, it is appropriate to investigate the complexity and costs associated with observations of Solar System objects.

We carried out a study from the perspective of the JWST Science and Operations Center (S&OC) to estimate the costs to the S&OC for supporting observations of moving targets. This study addresses only ground system costs and does not include the costs of any new requirements that may need to be levied on the flight software or hardware. Other elements of the JWST project will need to conduct similar studies to arrive at the total cost of a moving target program.

To facilitate this investigation, we (1) developed an operations concept for observing moving targets, (2) determined the requirements needed to support the concept, and (3) derived an estimate of the cost associated with meeting these requirements. The concept we adopted attempts to minimize additional complexity in the ground system and new requirements on the flight software without precluding observations of any moving target that can be supported within flight hardware limitations. Furthermore, moving target capabilities from the HST ground system have been adopted to the fullest extent possible.

This report is organized as follows. Section II provides an overview of the issues to be considered when observing moving targets. We discuss the range of angular velocities that Solar System objects may have when they are observable by JWST, and how this, along with the JWST ephemeris, effects the preparation, planning and scheduling of moving target observations, most notably with regard to the selection of a guide star. In the context of JWST's event driven schedule, we discuss the impact to observatory's efficiency when Solar System observations populate the queue. Section III outlines the moving targets operations concept we adopted for this study. The assumptions upon which this concept is built are itemized. All new requirements on the proposal preparation, planning, and scheduling systems are identified (but not reported in this document). Section IV reports the estimated costs to the S&OC to implement these requirements and to support operations associated with moving target observations. Section V summarizes the results of this study.

II. Preparation, Planning, and Scheduling JWST Moving Target Observations

Event Driven Scheduling

The operations concept for JWST does not call for observations to be scheduled at fixed, absolute times. Instead, observations will be scheduled as “visits” that execute within plan windows. Each plan window will contain a single visit. The visit will contain the slew to the target, the guide star acquisition, target acquisition, and all of the individual exposures and dithers. To allow for flexibility, and to avoid the need for the ground system to accurately predict when events on orbit will actually occur, the plan window will generally be larger than the visit length. In order to optimize the efficiency of the observatory, plan windows will overlap, although visits will not. In this event driven schedule, a visit can begin as soon as the previous visit in the queue is completed. This minimizes the incidence of idle gaps in the observatory’s activities. For example, if the guide star acquisition fails for a visit, the flight software will execute the next visit in the queue at the earliest possible time, which would be immediately if there are no visit specific restrictions to the contrary. If all of the visits in the queue have sufficiently flexible start times, then no gaps due to visits that complete early or fail will materialize. On the other hand, visits with time constraints might not be able to execute early enough to close such gaps, implying a potential loss of observatory efficiency when they populate the schedule.

Scheduling Moving Target Observations

Unlike targets at great distances, Solar System bodies can move a significant distance across the celestial sphere on time scales that are meaningful for planning an observation. If a JWST observation of such a body requires that its image remains fixed within a science instrument’s aperture, the spacecraft will need to track the object at the appropriate rate and in the appropriate direction. This implies that the guide star, which is fixed on the sky, will move along a path in the fine guidance sensor (FGS).

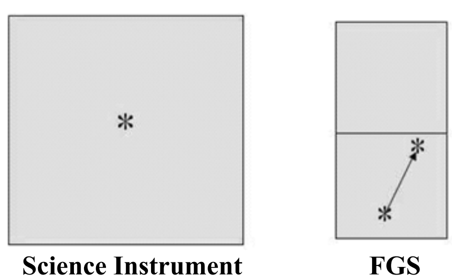

Figure 1. A guide star’s position will move along a path in one of the FGS’s 2’x2’ detectors as the spacecraft tracks a moving target to maintain its image at a fixed location in a science instrument’s aperture.

The proposed FGS design is a pair of 2kx2k infrared detectors, each with a 2’x2’ field of view (FOV). The guide star’s position is determined by reading out a 4x4 pixel, 0.24”x0.24” sub array. During a visit only one detector will monitor the guide star’s position. Figure 1 illustrates the path a guide star might traverse across the FGS as the spacecraft tracks a moving target. The amount of time a that guide star is in the FGS FOV will depend upon the guide star’s path across the FGS and the angular rate of the target being tracked. This is one factor in determining the duration of a moving target’s plan window.

Table 1. Angular rates of selected Solar System objects as seen by JWST

Object	Min. Rate (mas/sec)	Max Rate (mas/sec)	Distance Traveled in 10 hrs at Min Rate (asec)	Time to Travel 1’ at Max Rate (hrs)
Mars	2	28.6	70	0.6
Jupiter	0.07	4.5	2.5	3.7
Jupiter, Io	0.004	10.2	0.14	1.6
Saturn	0.04	2.9	1.4	5.7
Uranus	0.02	1.4	0.7	17
Neptune	0.004	1.0	0.14	24
KBO (typical)	0.002	0.5	0.07	48

For a Solar System object orbiting within the ecliptic, its angular rate as seen by JWST will vary as a function of its distance and angle from the JWST-Sun line. Taking into account that the telescope is constrained to point no closer than 85° from the Sun and not more than 153° from the Sun, Table 1 lists the minimum and maximum angular rates of selected planets and satellites as seen by JWST over its field of regard. The fourth column lists the distance, in arc seconds, that a guide star would traverse across the FGS FOV in 10 hours if JWST tracks the target when it moves at the minimum rate. The fifth column shows the time it takes a guide star to travel 1 arcmin across the FGS, half the width of its FOV, when JWST tracks the target while it moves at its maximum rate. Figure 2 shows the angular speed of Mars, Jupiter, and Neptune as they traverse the JWST observing annulus. These results show that, depending upon when an observation is scheduled, the plan window can be on the order of days for observations of Solar System targets if guide star availability is the only constraint. Since the observations will typically be much shorter, scheduling visits of this nature should be similar to scheduling visits to fixed targets. Furthermore, if the exposure times or visits are sufficiently short, tracking may not be required.

However, if additional (target-local) time constraints apply, such as the need to observe the transit of Io through Jupiter’s magnetic flux tube, the plan window can become the same size as the visit length. With JWST’s event driven schedule, a time constrained visit like this might not be able to execute early enough to close gaps in the schedule created by visits upstream in the queue that completed early (or failed). In such instances this would degrade observing efficiency.

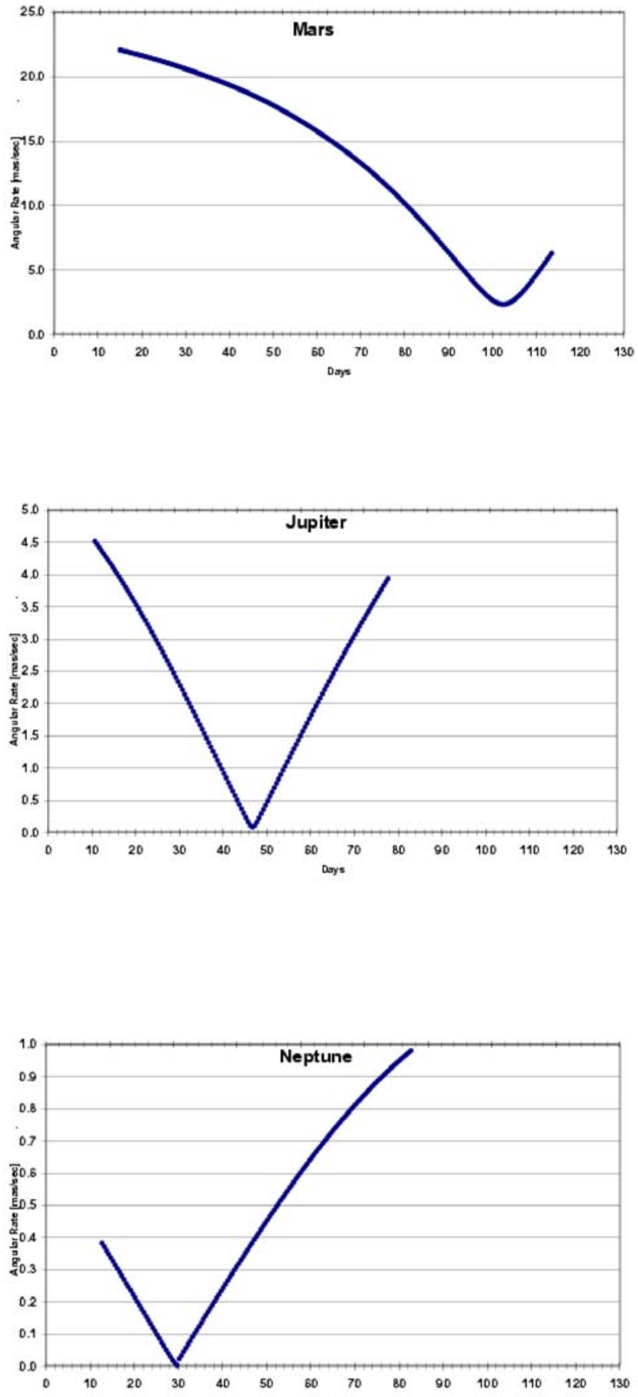

Figure 2. The angular rates (mas/sec) of Mars, Jupiter and Neptune as each object traverses the JWST observing annulus, assumed to be from 85° to 153° from the JWST-Sun line. In these particular examples the objects enter the JWST field of regard when they are 85° from the Sun.

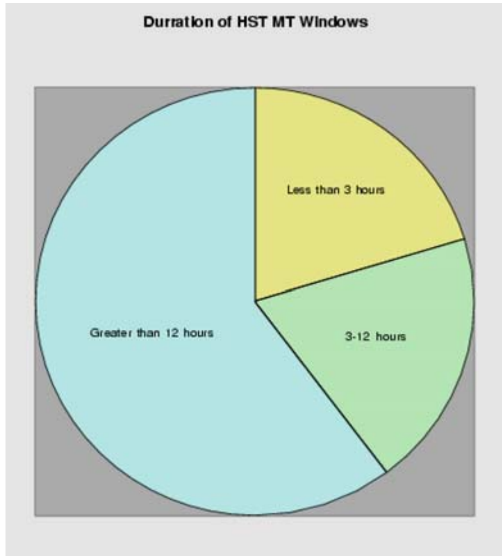

Figure 3. This diagram shows the distribution of target-local timing constraints on the observing windows for the HST Solar System program spanning early 2001 to late 2002. Observing the ingress of a satellite across a planet's disk is highly constrained, whereas obtaining a spectrum of Pluto's atmosphere is not. If this distribution were to hold for JWST, only about 20% of the Solar System program would have target-local requirements that might introduce gaps in the JWST schedule (and loss of observatory efficiency).

An estimate of the anticipated distribution of target-local time constraints for observations of Solar System objects is shown in Figure 3. These data are based upon statistics from the HST Solar System observing program spanning from early 2001 to late 2002. Displayed are the lengths of observing windows over which specific events can be observed (note this is not the exposure times or visit lengths). Scheduling constraints are more relaxed for the larger windows and more constrained for the smaller windows (obtaining a spectrum of Neptune's atmosphere vs. observing a satellite's ring crossing, e.g.). Only about 20% of the targets in this sample are significantly constrained relative to other scheduling considerations. If this distribution is to hold for a JWST Solar System program, which is not expected to use more than a few percent of the telescope's time, the impact to the observatory's efficiency should be small.

Preparing Moving Target Proposals

For HST, the periodic Earth occultations and SAA passages, both of which cause cessation of observations, convolved with guide star availability, significantly reduces the number of opportunities to observe certain phases of target-local events, such as the ingress or egress of a satellite across a planet's disk. HST observations of non time critical, long duration events, for example the mapping of a planet's surface while the body rotates, are also complicated by observing from low Earth orbit; the result is time constrained multi-orbit visits that are difficult to schedule around SAA passages. JWST's uninterrupted L2 viewing point will mitigate much of the scheduling difficulty that has plagued observations of Solar System objects with HST.

Table 2. Positional uncertainty of various objects with a 10% JWST ephemeris error.

Object	Positional Uncertainty (asec)
Jupiter	24
Saturn	13
Uranus	5
Neptune	2
Pluto	1
KBO	0.7

However, the uncertainty of the predicted JWST spacecraft ephemeris may complicate the preparation, planning, and scheduling of visits to Solar System objects. The position and rate of a Solar System object projected on to the celestial sphere, as seen by JWST at the time of the observation, will depend upon its ephemeris and the JWST ephemeris. Table 2 lists the uncertainty of an object's position (as seen by JWST) if the spacecraft's location in its orbit about L2 is uncertain by 10% (80,000 km), as it might be at proposal preparation time one year in advance. Since a proposal can be made flight ready no sooner than when the predicted JWST ephemeris (or the orbital elements of a comet) is sufficiently accurate to select the guide star, some moving target proposals, perhaps only those observing objects closer than Saturn, or comets, are likely to require replanning prior to scheduling. This adds operational costs to the S&OC. We note that the spacecraft's predicted ephemeris is expected to be sufficiently accurate to support the selection of the guide star a few months in advance.

Executing Moving Target Observations

With the possible exception of Kuiper belt objects, observations of moving targets will require enhancements to both the ground system and the flight software. To observe a Solar System object, the flight software determines the time dependent offset of the target from the guide star and commands a spacecraft maneuver to place the target at the desired location in a science instrument's aperture. If need be, the flight software causes JWST to track the target to maintain the location of the object's image in the aperture. The data needed to determine the target's instantaneous offset from the guide star and the required tracking rate are provided by the ground system, perhaps in the form of a polynomial representation of the target's position as a function of time.

Data Analysis and Data Archiving Moving Target Observations

With regard to the calibration or removal of instrument signatures, observations of moving targets present no additional requirements beyond those necessary for fixed targets. No unique data reduction requirements for pipeline processing are expected.

Classes of Moving Targets

Table 3. Ascending levels of complexity for observing moving targets

Object	Position	Tracking	Advanced Scheduling	Moving Target Enhancements	
				Ground System	Flight Software
Star, Galaxy	R.A., Dec	no	year	no	no
KBO	Ephemeris	no	year	yes	no
Object, rate $<\mu$	Ephemeris	no	many months	yes	no
Object, rate $>\mu_0$ distance $> d_0$	Ephemeris	yes	many months	yes	yes
Object, rate $>\mu_0$ distance $< d_0$	Ephemeris	yes	few months	yes	yes
Comets	Orbital Elements	yes	weeks or days	yes	yes

Table 3 summarizes the levels of complexity associated with observations of Solar System targets. Clearly, observations of comets are more complicated than Kuiper belt objects, which in turn are only marginally more complex than observations of fixed targets. The value of the angular rate μ_0, which sets the need to track the object, depends upon details of the visit. For example, if a target moves only 4 mas during a NIRcam exposure, corresponding to only 0.1 pixel, tracking might not be needed. The distance d_0 of an object determines the time at which a proposal can be made flight ready. As discussed earlier, this is dominated by the uncertainty of the JWST predicted ephemeris (which delays selection of a guide star). Like wise, an observation of a comet might not ready for execution until just a few days before hand, when its orbital elements can be predicted with sufficient accuracy to select a guide star.

An operations concept for observing moving targets is presented in the next section. In conformity with the scheduling approach used for observing fixed targets, the concept assumes that only one guide star or set of guide stars will be specified for each visit, and all of these guide stars will be valid for the entire plan window. Furthermore, each plan window will contain just one visit.

This concept is not optimized for observing fast moving objects, such as comets. If the scientific objectives cannot be achieved over the time that a guide star remains within the FGS FOV, additional plan windows and visits, each with new guide stars, can be scheduled to secure the necessary data. Although this will require increased support from the S&OC, no new ground system or flight software capabilities are required beyond that which is needed to support observations of slower objects. An alternative would be to add complexity to the ground system and flight software to support the use of several time tagged guide stars within a visit and plan window. However the cost associated with this approach, which we have not estimated, may not justified if this capability is rarely needed. If observations of fast moving comets will be common, this alternative can be revisited at a future date.

III. Observing Moving Targets with JWST, An Operations Concept

This section specifies an operations concept for observations of Solar System targets with JWST. The scope of this concept includes proposal preparation, planning, scheduling, execution, and data archiving. The assumptions around which this concept has been built are itemized below. The requirements derived from this concept have been identified (but not reported in this document) and the costs associated with their implementation are estimated. Extensive use of existing capabilities from the HST ground system has been assumed. In particular, this includes the Astronomer's Proposal Tool (APT) and the Moving Object Scheduling System (MOSS).

The main objective of the concept is to identify a process whereby observers generate an observing script for moving targets that can be efficiently and economically processed and scheduled by the S&OC and safely and economically executed by JWST, resulting in archived data sets of high scientific value.

The operations concept for observing moving targets is built around the following assumptions.

(1) All observatory level restrictions applicable to fixed target observations will apply to moving target observations.
(2) The science instrument modes and target acquisition schemes that are used for fixed targets will suffice for moving target observations.
(3) JWST has the ability to track targets.
(4) The JWST ephemeris is known with sufficient accuracy to allow for the selection of guide stars in advance of the date of observation.
(5) Only one guide star or set of guide stars will be identified and used for a visit. All shall be within the same FGS detector for the duration of the plan window.

A high level overview of the ground system architecture for proposal preparation, planning and scheduling is shown in Figure 4. Unique to moving target proposals is the need to access the JWST ephemeris and target ephemeris to determine the usability windows for the candidate guide stars.

Proposal Preparation

The S&OC will provide observers with a standard proposal preparation template. Using this template, a proposer generates an observing script that identifies the specific requirements for the visit(s) which must be met to achieve the observer's scientific objectives. For fixed targets this will include the object's position, its spectral colors and magnitudes, classifying it as a star or galaxy, etc. For Solar System objects, this template will allow the observer to flag the target as a moving target, and if appropriate, define it as a standard object (such as a planet, or a planet's satellite). The S&OC will provide the ephemeris of all standard objects. The observer will specify the orbital elements for non-standard objects.

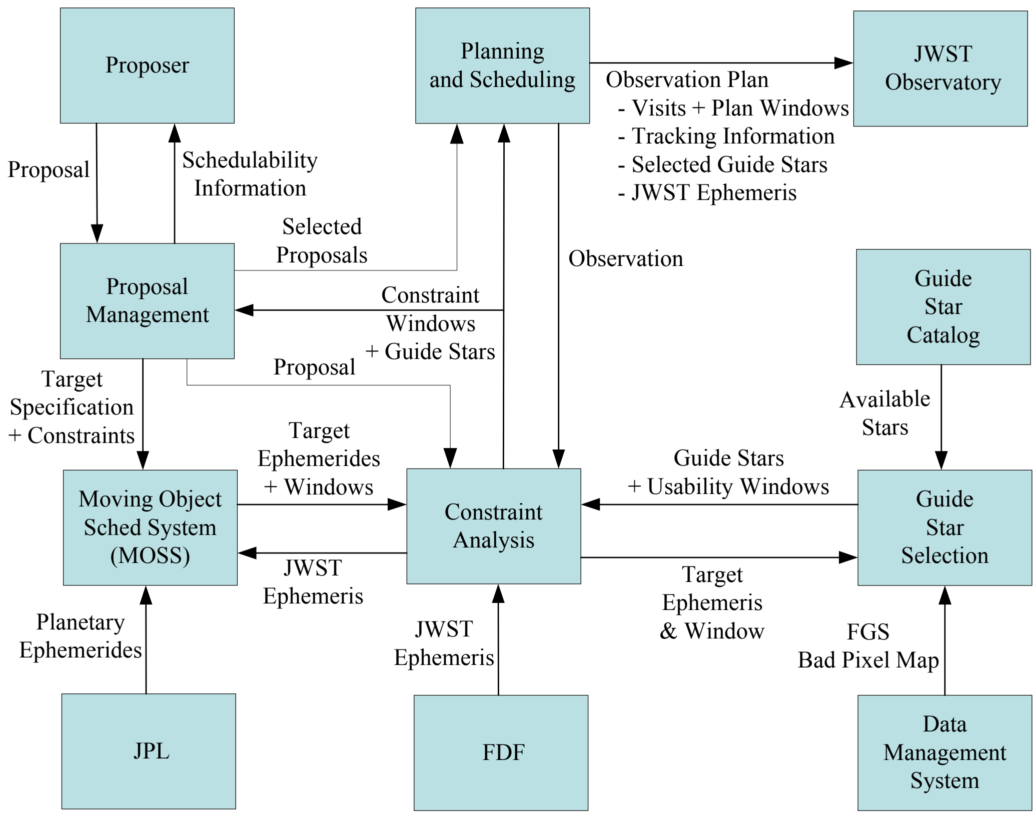

Figure 4. Displays a high level diagram of the proposal preparation, planning, and scheduling system in the concept adopted for this study. Note that the proposer builds the proposal with the same constraint analyzer that is used by the planning and scheduling system. For moving targets, the target and spacecraft ephemeris are needed for the guide star selection.

The proposal preparation template will support the specification a variety of target-local attributes, such as the central meridian longitude (CML) or a particular phase of a periodic event, to define the pointing and constrain the time of observation. All capabilities provided for fixed targets, such as target acquisitions and offsets, dithers, special orientations, science instrument modes, filter selection, and exposure times will be available for moving target observations. All observatory level constraints applied to fixed targets will apply.

The S&OC will provide the observer with access to a proposal processing package that interprets and processes the instructions and requirements specified on the standard proposal template. This package will inspect the proposal for completeness, check for violations of observing constraints, calculate exposure and visit level overheads, and determine when the moving target will be within the JWST field of regard.

Using the similar software employed by the S&OC planning and scheduling system (e.g., APT and MOSS), the proposal processing package will access the predicted JWST ephemeris, the target's ephemeris, the FGS bad pixel map, the guide star catalog, and the same set of guide star selection rules that are available to proposers preparing observations of fixed targets. This will allow the proposer to estimate the scheduling opportunities for the visit.

The output of the proposal processing package will specify the observing windows satisfying all user-specified and observatory constraints. Any constraint violations will be made known to the proposer. Proposals with unresolved conflicts will be noted as such upon submission to the S&OC.

Proposal Planning and Scheduling

The S&OC will accept and process a standard proposal from an observer. For fixed targets, the object's position will be specified by its coordinates in a standard reference frame (ICRS, e.g.). For moving targets, the S&OC will access either an ephemeris for standard targets, or accept the orbital elements for non-standard targets, such as a newly discovered comet, provided by the observer. For scheduling, all constraints applied to observations of fixed targets will remain valid, plus the requirement that the guide star is usable (within the FGS FOV, e.g.) for the entire plan window. If a proposal is determined to be unschedulable, the S&OC will initiate a process with the proposer to resolve the conflicts.

Consistent with the JWST event driven schedule, the visit may execute over a range of times within the planning window. The proposal planning and scheduling system will determine the appropriate coefficients for a polynomial representation of the moving target's position as a function of time over the course of the planning window. The scheduling system will make this representation available to the flight software so that it may direct the spacecraft to acquire and track the target.

Flight Software

The ability to track moving targets adds new requirements to the flight software. (The cost to meet these requirements is not estimated in this study.) The flight software will have the ability to cause JWST to acquire a fixed guide star and to re-point the telescope to place the image of the target at the desired location in a science instrument's aperture. For fixed targets, this maneuver will be determined by the fixed offset between the guide star and target. For moving targets, the flight software will compute the time dependent offset between the target and the guide star. If necessary, the flight software will cause the spacecraft to commence tracking once the target is correctly placed in the desired aperture. The flight software will have available from the planning and scheduling system a polynomial representation of the target ephemeris as seen from JWST. It is expected that the flight software will use this ephemeris data to update the target's position at a TBD rate in order to maintain tracking. The moving target requirements levied on the flight software are:

(1) After acquisition of the guide star, the flight software shall upon receiving a "start moving target track request" command a spacecraft slew to place the moving target at the desired location in the JWST focal plane and commence tracking. The data needed to determine the maneuver and tracking rate will be provided by the ground system as a

polynomial representation of the target's position as a function of time.

(2) The flight software shall use this polynomial to update the tracking rate and direction as a function of time. The updates will occur at a TBD rate.

(3) The flight software shall cease moving target tracking upon receiving a "stop moving target track request".

Data Processing and Archiving

Observations of moving targets are not expected to require any special calibration pipeline processing, nor require any special preparation prior to archiving beyond what will be done for observations of fixed targets.

IV. Cost to the Science & Operations Center

The new requirements placed upon the ground system (proposal preparation, planning, scheduling, and guide star selection subsystems) to implement the moving target operations concept have been identified. (The requirements are not reported in this document.) Using the Cost Expert analysis package, the cost to the S&OC for the development, integration and testing, and maintenance of the software needed by the ground system to meet these requirements has been estimated. Where possible, reuse of capabilities from the HST ground system has been assumed. This includes significant components of APT and MOSS. Additional costs associated with operations have also been estimated. These include user support, documentation, and activities associated with proposal planning and scheduling.

We have identified the new functionality required in APT. For preparing moving target proposals this includes access to the spacecraft ephemeris, the preparation of scripts to be executed by MOSS, an interface to MOSS, and a display tool that allows the tracking data returned from MOSS to be projected against the guide star catalog.

The Cost Expert package estimates the number of single lines of code (SLOC) needed to implement the requirements of the concept. Table 4 itemizes the Cost Expert estimates of the growth in the Planning and Scheduling System and Guide Star Selection System. Columns 3 and 4 show the new and re-used (from the HST ground system) SLOC for each subsystem in the S&OC baseline proposal (for observations of fixed targets). Column 5 shows the new SLOC estimates for processing moving target proposals, and column 6 shows the percent increase in the size of each subsystem. The growth in SLOC for the Planning & Scheduling System and Guide Selection System is estimated to be 12%.

Table 5 itemizes the estimated yearly total cost to the S&OC for supporting moving target observations based upon the concept adopted in this study. This includes costs for software development, maintenance, integration, and regression testing, for the APT, the

Table 4. Costs to the Planning and Scheduling Subsystems for Observing Moving Targets

		Baseline Proposal (Fixed Targets)		Delta, Moving Targets		Comments
Subsystem	**Component**	**New Code**	**Reused SLOC**	**New Code**	**% Change**	
Planning & Scheduling Subsystem						
	FOV Tool	20000		4000	20	Display guide stars moving through FOV
	Obs Spec. Translation	30000		3000	10	Added complexity
	OP Verification	30000		1500	5	Added complexity
	Planning Engine	30000	70000	6000	6	Significant changes
	PPS GUI	10000	10000	200	2	Minor enhancements
	Proposal Tracking	10000		500	5	Minor enhancements
	PS Reports	10000		500	5	Specific reports
	Scheduler	40000		8000	20	Significant changes
	Utilities	20000	15000	2000	10	Additional utilities
	MOSS, for moving targets		450000			Major regression & integration testing
Total		**200000**	**95000**	**25700**		Moving targets add ~9% to the P&S fixed targets proposal
Guide star Selection Subsystem						
	Guide star Selection		50000			
	JWST Guider Issues	20000		20000	100	Moving Targets double the SLOC for Guide Star selection.
Total		**20000**	**50000**	**20000**		

Planning and Scheduling System, and the Guide Star Selection System, as well as the cost for one year of operations. (We assumed that the launch of JWST will occur in 2010.) This cost is estimated to be $2.73M. Afterwards, when all development and testing is completed, we estimate the cost for operations and software maintenance to be $254K/year. The cost of the development phase represents a 5% increase in the baseline (fixed targets) S&OC proposal. The cost of the operational phase represents an increase of 3%.

Table 5. Estimated yearly costs to the S&OC for supporting moving target observations.

2005	2006	2007	2008	2009	2010	2011	Total
327,686	339,493	351,126	572,993	407,863	478,042	254,187	2,731,380

V. Conclusions

We carried out an investigation to estimate the cost to the S&OC for the development and maintenance of the enhancements needed by the ground system to support observations of moving, Solar System targets with JWST. We have identified how moving target observations differ from those of fixed targets. We have considered the range of angular velocities that a variety Solar System bodies in the ecliptic may have when they are observable by JWST. We believe that the scheduling of moving target observations will be easier with JWST at L2 than with HST in low Earth orbit. However, moving target observations will be more complicated to prepare, plan and schedule than observations of fixed targets, and will place new requirements on the ground system and the flight software. Although there is a potential for moving target observations to result in a loss of observatory efficiency, we conclude that such losses are likely to be insignificant.

To facilitate a cost analysis, we adopted an operations concept for observing moving targets. In this concept the astronomer prepares a moving target proposal using tools similar to APT and MOSS. The Planning and Scheduling System, with access to the target and spacecraft ephemeredes, generates a flight ready proposal and provides the flight software with a polynomial representation of the target's position as a function time. The flight software makes use of this representation to command the observatory to acquire and track the object over the course of the observation. This concept imposes a minimum number of new requirements on the ground system and flight software, but yet in principle supports the observation of any moving target. Restrictions imposed by the flight hardware will ultimately determine which Solar System objects can be observed by JWST.

We have identified the requirements needed to implement this moving target concept. We have used the Cost Expert analysis package to estimate the growth in APT, the Planning and Scheduling System, and Guide Star Selection System needed to meet these requirements. The costs for software development, maintenance, integration and testing, as well as daily operations have been estimated. We estimate the total cost to the S&OC for developing the necessary infrastructure for supporting observations of moving targets, and for providing one year of operational support, to be $2.73M. Once all development and testing is completed, the operational cost, which includes software maintenance, is estimated to be $254K/year. For the development phase, this represents an increase of 5% in the S&OC proposal for observing fixed targets. The operational phase represents a 3% increase. The total cost for supporting a JWST moving targets program can be estimated only after all relevant elements of the project undertake a similar study.