Moving Target Working Group: Final Report

JWST-RPT-009982

Date: 19 November 2007

Contributing Authors:
S. Anandakrishnan
V. Balzano
S. Casement
J. Isaacs
K. Long
F. L. Markley
E. Nelan
C. Rui
G. Sonneborn

Table of Figures

Table of Tables

1 Introduction

1.1.1 Study overview

This report presents the conclusions of a three-month study conducted from mid-July 2007 to mid-October 2007 to develop a conceptual design to provide a moving target capability for JWST, and to provide cost estimates for implementing this capability. The study was authorized by the NASA Science Mission Directorate and has been led by Mission Systems Engineering, specifically by the Pointing and Control Lead Engineer of this group, with representation from the Lead Software Engineer and in conjunction with JWST Project Scientists. The Space Telescope Science Institute (STScI) documented a previous investigation of the moving target tracking capability in STScI-JWST-R-2002-006A in November 2002. This study was supported by STScI, the FGS team, and NGST to provide a technical implementation baseline across the observatory.

The mid-October completion date is sufficiently before the Program PDR / NAR so that NASA can make a decision whether to authorize this implementation and its costs in time for the Project to make the appropriate additions to its PDR package.

The ground rules for the study were as follows:

- Only linear motion will be considered
- Each observation will require only a single guide star
- The capability will be engineered for the following baseline requirements:
    - Tracking Rates of up to 3 mas/sec
    - Pointing Stability of 50 mas (3 sigma) for 700 second observation
- The performance will be characterized for rates as high as 30 mas/sec

A Moving Target Working Group (MTWG) was organized, with a kickoff meeting on July 24, 2007. The MTWG has held weekly teleconferences, and an all-day Technical Interchange Meeting (TIM) at NGST Space Park on August 22, 2007 at which the technical baseline for the moving target capability was established.

1.1.2 Conclusions of Study

The scientific argument for implementing a moving target tracking capability on JWST is compelling. The near and mid-IR performance of JWST will be unique in its power to probe Pluto and other Kuiper Belt Objects (KBOs), the icy moons of the giant planets, and comets, and to understand their role in the evolution of the Solar System.

The technical baseline for implementing this capability uses existing Ground & Flight Segment fixed target capability to the greatest extent. All observational restrictions applied to fixed targets also apply to moving target observations.

JWST can observe a moving target whose motion is specified by an ephemeris. This ephemeris is converted to a linear path for the guide star location in the Fine Guidance Sensor guider coordinates, so that the science target will remain fixed at the desired SI aperture location to first order if the guide star is held to this path. Only one guide star used for a visit, and it stays in the same FGS detector for the duration of the visit. Multiple guide star candidates may be provided for moving targets, as provided for fixed targets to allow for ID and ACQ failures. A difference is that the guide stars for moving targets may not all be valid for the entire plan window, so the guide star is selected based on when the visit is to be executed onboard, increasing the visit window and maintaining the event-driven observation paradigm.

The Flight-Ground and ISIM-ACS command, telemetry, and data interfaces have been defined. The onboard implementation of the moving target tracking capability involves both the ISIM on-board scripts and the ACS. Moving target rates of up to 30 mas/sec can be achieved in the same manner as 3 mas/sec. The pointing budget meets 50 mas (3σ) requirement, with margin, at maximum rate of 30 mas/sec. The FGS already meets its noise-equivalent-angle (NEA) requirement at this rate. No hardware modifications and very few new or modified onboard commands are required. The FGS must accept a new command to set an 8x8 Track box for moving targets, but this is very similar to setting an 8x8 Fine Guide box for fixed targets.

Verification will be by analysis and simulation, and will closely parallel the verification of fixed target tracking.

1.1.3 Process forward

At the completion of the study, the conclusions and cost estimates will be presented to the NASA Science Mission Directorate to inform a decision whether to authorize this implementation, with the desire that this decision be in time for the Project to make the appropriate additions to its PDR package.

2 Scientific Justification

2.1.1 Background

JWST will be key for understanding the physical characteristics of cold bodies at the edge of the Solar System. These objects include Pluto and other Kuiper Belt Objects (KBOs), the icy moons of the giant planets, and comets. Recent discoveries of large objects in the Kuiper Belt, along with many smaller members, make it clear that this region represents a major constituent of our Solar System, one that was hidden until recently because it is so remote and challenging to observe. Similarly, a new class of comets that exist as part of the main asteroid belt between Mars and Jupiter was discovered in 2006. The near and mid-IR performance of JWST will be unique in its power to probe these objects and understand their role in the evolution of the Solar System.

2.1.2 Objects that comprise the “moving targets” and why they are important

2.1.3 Kuiper Belt Objects

The KBOs reside beyond the orbit of Neptune (30 AU) and have apparent rates of motion of 1 milli-arc seconds (mas) per second or less relative to the inertial reference frame (guide stars). Several related objects, such as the dwarf planet Pluto and Neptune’s large moon Triton, itself probably a captured KBO, have slightly higher rates: up to 3 mas/sec. KBOs have a size distribution. There are now several ~1000-km diameter objects known, including Pluto, and a total of about 1000 smaller KBOs known (down to *d*~30 km) that have reasonably well-determined orbits. JWST will have the ability to obtain R=100 near-IR spectra and 20–25 mm mid-IR photometry of all known KBOs. These smaller objects are essential for understanding the compositional differences and origin of the Kuiper Belt.

The wide range of optical properties and albedos of KBOs is likely to result from both surface "weathering" and from the existence of a number of distinct KBO classes, perhaps related to their origin from distinct parent bodies. This ambiguity can be resolved with near and mid-IR narrow band imaging and spectroscopy of many KBOs. Near-IR spectra of KBOs will record the reflected solar spectrum to identify surface constituents, such as water ice, hydrocarbons (propane, ethane, etc), water hydration bands, and nitrile compounds. Mid-IR spectra and imaging of KBOs longward of ~20 microns will record the intrinsic thermal radiation from the object (as opposed to reflected sunlight at shorter wavelengths). Comparison of 20 and 25 micron photometry of a KBO will determine its albedo, and hence its diameter. Comparison of the composition of surface ices of KBOs is crucial to understand whether the short-period comets originate in the Kuiper Belt. Similarly, comparison of KBOs to debris disks around other stars is key for connecting the Kuiper Belt to equivalent regions around other stars.

Spitzer has observed several of the brightest KBOs but does not have the sensitivity to detect additional objects. The faintest of the KBOs has a visual magnitude V~25 (flux density of 200-300 nJy at 2-3 microns). With an albedo of ~10%, this corresponds to a diameter of 20-30 km, which is close to the size of a comet nucleus.

Pluto is the benchmark object in the outer solar system and has well-measured near- and mid-IR brightnesses. The 100-km class objects are much fainter than Pluto. Having 10% of Pluto's diameter and being further away (~45 AU vs. 30 AU for Pluto), the small KBOs have less than 1% of Pluto's brightness. This means that the smaller KBOs have flux densities of ~1 μJy longward of ~4 μm, or fainter if the surface albedo is less than Pluto's.

2.1.4 Comets

Comets are remnants of Solar System formation, and their current composition and physical properties provide a constraint on the conditions in the solar nebula 4.6 billion years ago. Comets were the building blocks of the giant planets' cores. Low resolution infrared spectroscopy of cometary dust will uncover mineralogical signatures, which can be compared with those seen in protostellar and planetary debris disks around nearby young stars and solar analogs, and potentially reveal the isotopic ratios of some major elements. Many comets fall within the maximum moving target rate studied for JWST (30 mas/sec). An important example is Comet 67P/Churyumov-Gerasimenko (C67P/C-G).

The International Rosetta Mission, the Planetary Cornerstone in ESA's long-term space science program, will rendezvous with C67P/C-G in mid-2014, making this object one of great scientific potential for JWST. Rosetta will study Comet 67P/C-G nucleus and its environment in great detail for a period of nearly two years prior to the 2014 rendezvous. After reaching Comet 67P/C-G, the spacecraft will spend one year mapping and examining the surface using remote sensing, analyzing dust and vapors, and releasing a 100-kg lander equipped with a drill and scientific instruments for in situ analyses. C67P/C-G belongs to the Jupiter family comets, which represents a large group of the short-period comets (P<20 years) in the Solar System that are dynamically controlled by the giant planet.

Analysis of the orbit of C67P/C-G shows that it is observable during key portions of the mission. Table 2-1 shows an example of the ephemeris of C67P/C-G as seen from JWST at L2 for August through October 2014. The comet's apparent rate of motion has a maximum of 7.2 mas/sec during this period.

Table 2-1 Comet 67P/C-G Ephemeris for JWST during Rosetta Encounter

Date (UT)	RA	DEC	$\Delta\alpha$ (arcsec/hr)	$\Delta\delta$ (arcsec/hr)	Rate (mas/sec)
2014-Aug-19 00:00	18 43 50.69	-31 02 28.0	-19.41	1.54	5.41
2014-Aug-29 00:00	18 38 57.80	-30 53 30.2	-11.85	2.86	3.38
2014-Sep-08 00:00	18 36 31.37	-30 40 08.0	-3.84	3.76	1.49
2014-Sep-18 00:00	18 36 34.37	-30 23 47.3	4.13	4.37	1.67
2014-Sep-28 00:00	18 39 02.01	-30 05 22.0	11.74	4.83	3.52
2014-Oct-08 00:00	18 43 44.82	-29 45 11.8	18.81	5.26	5.43
2014-Oct-18 00:00	18 50 31.09	-29 23 08.8	25.26	5.78	7.20

Observations of comets with JWST will enable investigations of the chemical composition of cometary ice and dust with unprecedented sensitivity. Near- and mid-IR spectroscopy of cometary comae can be used to measure abundances of H_2O, CO, CO_2 , and CH_3OH in even relatively faint comets. Near-IR spectrometry with R ~ 1000 resolution will be used to measure the ratio of ortho-to-para H_2O (OPR) separately, possibly providing an indication of the comet's formation temperature. Likewise, mid-IR spectroscopy can determine the mineralogy of cometary dust grains. Finally, JWST's ability to image cometary nuclei at both mid and near-infrared wavelengths with high spatial resolution and sensitivity will allow high accuracy measurements of sizes and albedos of cometary nuclei. The results from cometary programs can be combined with those from programs investigating circumstellar disks and star formation regions to build a complete picture of planetary system formation and evolution.

JWST will measure the CO_2 abundance in comets that come within ~3 AU of the Earth and Sun. Such measurements cannot be done from the ground because of CO_2 in the Earth's atmosphere. Depending on the circumstances, JWST can measure CO_2 emission in either the ν_3 band near 4.3 μm or the ν_2 band near 15 μm, both of which are exceptionally strong. The CO_2 molecule must be detected from space because strong absorption in the terrestrial atmosphere prevents ground-based IR observations, and its lack of a permanent electric dipole moment molecule precludes radio emission.

2.1.5 Main Belt Comets (Icy Asteroids)

Astronomers have known for more than two centuries that comets can be split into two groups as defined by their orbits about the Sun. Long-period comets (P>200 years) originate from the Oort Cloud. Jupiter-family comets (P~20 years) originate from the region beyond Neptune. A new third dynamical class of comets, recognized only in 2006, orbit much closer to the Sun entirely within the main asteroid belt. These are referred to as the main belt comets – faint icy asteroids that have dusty eruptions producing cometary comae. These objects are of particular interest as

they could have been an important source for terrestrial water delivered to the Earth early in its history. JWST is the only means to characterize the chemical properties (water, hydrocarbons, mineralology) of this new class of comets. Their apparent rates of motion are intermediate between Mars and Jupiter (see
).

2.1.6 Planets and Their Satellites

JWST has great potential to expand our knowledge of the planets, and their satellites, beyond the earth's orbit. The rates of motion of the planets are summarized in
. Here are three examples – Mars, Io, and Titan.

Table 2-2 Angular rates of selected Solar System objects seen from L2

Object	Minimum rate (mas/sec)	Maximum rate (mas/sec)	Distance moved in 10 hrs at min rate (arcsec)	Time to move 1 arcmin at max rate (hours)
Mars	2.5	28.6	90	0.6
Jupiter	0.070	4.5	2.5	3.7
Io	0.004	10.2	0.14	1.6
Saturn	0.040	2.9	1.4	5.7
Uranus	0.020	1.4	0.7	12
Neptune	0.004	1.0	0.14	17
Pluto	0.160	1.0	5.7	17
KBO	0.002	0.5	0.07	33

Continued studies of Mars with JWST offer the promise of unique and important new contributions to Mars science and to NASA's future mission goals. Specifically, global-scale near-IR observations can: (1) determine the variability of atmospheric species like CO_2, CO, and H_2O, providing critical data for photochemical and dynamical modeling of the present Martian climate; (2) constrain the near-IR radiative and absorptive properties of airborne dust, another key component of the present Martian climate system; (3) assess the magnitude and scale of diurnal, seasonal, and interannual volatile transport through direct near-IR detection and discrimination of surface and atmospheric H_2O and CO_2 ices/clouds, especially in the polar regions; (4) help to quantify the surface volatile budget and resource potential by detecting and mapping the distribution of H_2O-bearing or OH-bearing surface minerals like clays and hydrates; and (5) enable the possibility of unlikely but potentially spectacular discoveries on Mars associated with thermal emission "hotspots" or the presence of organic (C-H bearing) minerals on the surface.

Io's allure is its very unusual nature as the most volcanically active body in the solar system, and its direct links to both the Jovian magnetosphere (through its associated plasma torus) and the Jovian atmosphere (via the strong current system that links the two). Detection of SO_2 gas absorption at 7.4 µm—seen by Voyager IRIS but not recorded since—will be of great interest because it records gas abundance directly above hot spots. This band cannot be observed from the ground due to telluric absorption, and while SOFIA can detect the band, it can't spatially resolve Io's disk. The mid-infrared spectroscopic capabilities of JWST would also be very useful for exploring subtle 10-20 µm spectroscopic features seen by Voyager IRIS. Furthermore, detection of faint, very high temperature hot spots at 0.6 - 1.4 µm would be of some importance, as would detections of neutral S emissions at 1 µm.

Titan is one of a triad of targets of high astrobiological interest in our own solar system, the other two being Mars and Europa. Of the three it has the densest atmosphere (four times the density of sea-level air on Earth), and is the most richly endowed in organic molecules on the surface. Its nitrogen-methane atmosphere, by virtue of continuous loss of hydrogen liberated from photolyzed methane in the upper atmosphere, is not strongly reducing, and hence is comparable to the pre-biotic Earth's atmosphere in net redox propensity for synthesizing organic polymers. While the chemistry of the atmosphere is well known, that of the surface is not. Spectral resolution a factor of 10 better than on Cassini can be accomplished using the NIRSPEC, allowing for spectra far more diagnostic of the types of organic species present on the surface. Thus while Cassini gets better spatial resolution, JWST will achieve higher spectral resolution and good spatial resolution over the mid-latitudes regions of Titan. Of additional interest is whether surface changes or secular atmospheric changes are in evidence over a decadal timescale.

2.1.7 Observation and Pointing Requirements

Near-IR intermediate band imaging (e.g. NIRCam methane filter, F250M, or the TFI) requires that the JWST pointing control system keep the KBO within one point-spread function (PSF) during the length of time for the instrument to reach the sky limit. For NIRCam F250M this is 700 seconds. The PSF is ~70 mas at 2 microns. Therefore, the pointing stability requirement derived for this example is to **hold a target moving at a non-inertial rate of 3 mas/s or less within 50 mas (3 sigma) of its initial position during a 700 second integration.** The target motion on the sky during the 700-second interval would be 2.1 arc seconds (3 mas/s for 700 sec).

3 Overview of the Moving Target Scenario

To develop a concept to observe moving targets, the fixed target scenario was used as a “point of departure” to identify missing components. The intent was to identify the lowest cost technical solution that meets the requirements that informed the study. A key criterion was to avoid all “solutions” that require hardware changes of any kind to any subsystem as this would be prohibitively expensive given the maturity of the JWST architecture.

A moving target scenario was developed to identify the detailed interactions between the JWST segments and subsystems involved in moving target observations; (1) Ground segment, (2) the ISIM on-board scripts, (3) the Fine Guidance Sensor (FGS), and (4) the Spacecraft Attitude Control System (ACS). This scenario facilitated the development of a technical concept for observing moving targets with JWST, including the technical concept for the Science & Operations Center (S&OC) to support the planning and scheduling of moving target observations. The scenario is discussed in detail in Section 4.

At the start of the scenario analysis, it was decided to implement moving target tracking by specifying and tracking the corresponding motion of the guide star in the FGS. This decision maintains consistency with fixed target observations, since it is the guide star position and location within the FGS that is used to control pointing and specify slews and offsets for fixed targets.

An additional criterion for the scenario analysis was to maintain the flexibility of event-driven operations. This criterion minimizes the impact of moving target observations on fixed target observations by ensuring that the time at which the moving target observation is executed is flexible (barring any “target-local” constraints to the contrary, such as a moon’s transit across the disk of a planet). In particular, command sequencing in event-driven operations is controlled by telemetry response rather than estimated execution time.

Functions are allocated to S&OC, on-board scripts, ACS and FGS based upon these two criteria. The following sections describe the allocation of functions and additional requirements to the Observatory subsystems and S&OC, along with modifications to their interfaces to implement observations of moving targets with JWST.

3.1.1 Ground System

The S&OC is responsible for managing the ephemeris of the moving target. The target may be one of the standard planetary objects for which the ephemeris is provided by JPL. Otherwise, the proposer will specify the ephemeris, typically by a set of orbital elements. The S&OC will use the moving target ephemeris to prepare and plan the observation and to select guide stars for the observation.

The S&OC will convert the moving target ephemeris into a corresponding ephemeris for each guide star that describes its motion across the FGS detector, and calculate the time window(s) over which the guide star can be used to track the moving target, such that it remains within one FGS detector and does not encounter regions of bad pixels.

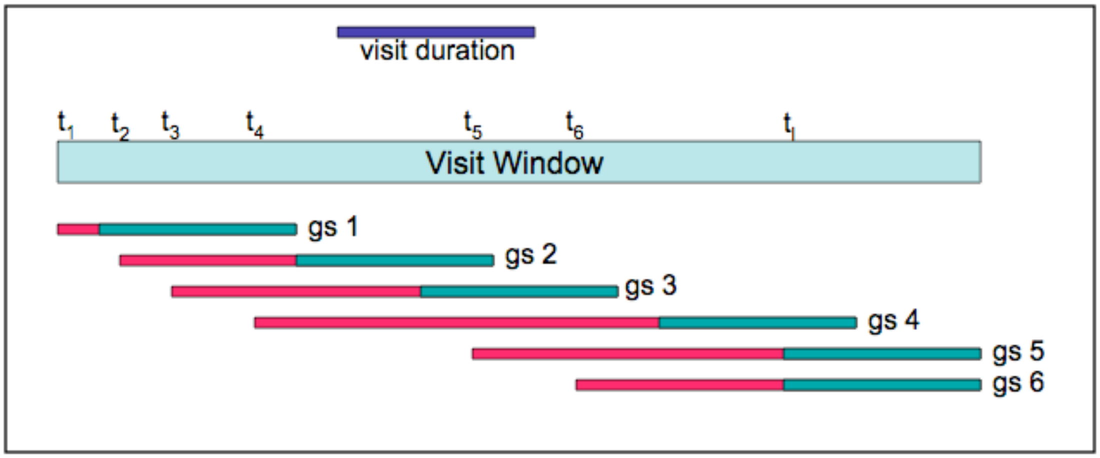

Figure 3-1 Guide Star Concept for Moving Target Tracking. The moving target visit window (light blue) can be made to be much longer than the visit duration (dark blue) by providing a set of guide stars with different usability intervals. In this diagram, t_1, t_2, t_3, t_4, t_5 and t_6 are the earliest start times of the visit when using guide star gs1, gs2, gs3, gs4, gs5, or gs6. The latest possible start time of the visit when using a particular guide star is marked by the time corresponding to the transition from red to teal along a guide star's usability interval. (The length of the teal is the visit duration.) The latest possible start time of the visit, t_l, may be determined by constraints other than guide star availability.

In order to preserve the event-driven operations paradigm, most observations should have a nominal observing window of at least one day. For the case of a target moving at 3 mas/second, a single guide star will typically remain in the FGS field of view (FOV) about 12 hours (depending on its path through the FOV). To ensure a high probability of successful guide star acquisition, up to three candidate guide stars should be available when the observation is executed (as for fixed targets). Thus, from 6-9 guide stars will typically be necessary to cover a nominal observing window of one day. For faster moving targets up to the desired 30 mas/second, a guide star is only in the FGS FOV for about 1.2 hours, so at least 60 guide star candidates would be required to cover a one-day observing window. As a result, the S&OC will uplink a list of guide stars, each of which can be used for the moving target observation at some time during a larger plan window (as graphically shown in **Figure 3-1**). Just as for fixed targets, reference stars and an identification and acquisition attitude will be specified for each guide star. The S&OC will also provide the usability window for each guide star in the list. The guide stars to be used for the visit will be selected by the on-board scripts based upon the time the visit is executed and the guide star's usability window.

The S&OC will calculate, from the moving target ephemeris, and for each guide star in the list, the track of the guide star across the FGS FOV that holds the target at a fixed location on a particular science instrument. As per the baseline requirements that informed this study, the guide track is approximated as a linear motion with a starting point P_0 at a time T_0 corresponding to some time within the guide star's usability window. While linear tracks will suffice for most objects (such as slow moving KBOs), it will break down for others, such as the moons of planets. While precluded by the baseline requirements of this study, a second or third order polynomial representation of a moving target's track is easily accommodated by the moving target scenario presented in this report. Moreover, the polynomial representation would simplify observations of objects such as Io in that a guide star's ephemeris would not need to be composed of piecewise segmented time-dependent tracks.

3.1.2 On-Board Scripts

The on-board scripts are responsible for generating commands to the ACS and FGS from the details provided in the Observation Plan, in order to execute slews, guide star acquisitions, and offset maneuvers for target acquisitions and dithers. All of these functions must be modified to support moving target observations.

The on-board scripts will accept a file containing a list of guide stars and their associated reference stars, acquisition attitude, usability window, and guide star ephemeris. When the on-board scripts are ready to execute the moving target observation, they will read the list until they find a guide star with a usability window that supports execution of the visit at the current time. If necessary, the scripts will wait until a guide star is usable. They will then use the information provided for the guide star to execute a slew to the acquisition attitude and attempt guide star acquisition. If the guide star acquisition fails, the scripts will repeat the process with another guide star for up to three attempts.

The on-board scripts will provide the guide star ephemeris to the ACS, and ACS will coordinate tracking with offset maneuvers for target acquisition and dithers. Based on ACS data, the on-board scripts will command the FGS into a "fine" track mode (instead of fine guide mode used for fixed targets) to control pointing during the moving target observation. Finally, the on-board scripts will coordinate knowledge of the guide star location after offset maneuvers between the ACS and the FGS, in order to set the FGS track box at the correct location to acquire and begin tracking the guide star.

3.1.3 FGS

3.1.4 Fixed-Target Scenario

The baseline Track function is optimized to support an efficient transition to the Fine Guide function, which is used to fine point the Observatory for visits to fixed targets. The FGS FSW sets up a 32x32 pixel sub array centered on the position provided by the scripts (which commands the FGS), as well as an 8x8 pixel sub array on the required location of the guide star for the anticipated Fine Guide function. The 32x32 pixel sub array is configured to be a "movable" sub array employing a 16 Hz Fowler-1 (CDS) readout strategy to obtain the image data for centroiding and following a potentially moving guide star. The 8x8 pixel sub array, or "Fine Guide box", is configured to be a fixed-location sub array that observes the guide star with a 16 Hz Fowler-4 readout strategy for centroid determination. Data from the 32x32 pixel sub array are used to provide guide star centroids to the ACS, which in turn are used in closed loop to eliminate pointing errors. When the on-board scripts receive notification from the ACS that the pointing error has been nulled, the scripts command the FGS to transition to the Fine Guide function (for fixed targets).

3.1.5 Moving-Target Scenario

For moving target visits, the FGS FSW requires a modified Track function. The 32x32 pixel sub array takes 16 times longer to read than an 8x8 pixel sub array, and most of the pixels are of no value for computing an accurate position of the guide star since they are read noise dominated.

To achieve the noise equivalent angle measurement of the guide star needed to meet the stability requirements, the FGS must use an 8x8 pixel sub array, just as for observations of fixed targets. Moreover, the 8x8 pixel sub array must be configured to be *movable* so that the FGS can "follow" the guide star along its ephemeris. Therefore, upon command from the on-board scripts, the FGS will transition from the 32x32 pixel sub array to the 8x8 pixel sub array while remaining in the Track function (rather than transitioning to the Fine Guide function). The FGS FSW requires a simple enhancement to accept and process this new command.

3.1.6 ACS

The required time-dependent location of the guide star on the FGS FOV is calculated by the ACS making use of the "guide star ephemeris" provided by the scripts. The ACS will use the guide star ephemeris in two ways, to (1) compute "corrections" to Small Angle Maneuvers (SAM) (ACS treats an offset or dither as a SAM) requested by the scripts, and (2) for updating the "commanded" position of the guide star at16 Hz in Fine Guidance. When the on-board scripts request a SAM, the ACS estimates the time it takes to execute the maneuver and settle at its completion. This estimate is added to ISIM overhead estimates (provided by the on-board scripts) to determine the maneuver that causes the guide star to intercept its ephemeris track when the FGS Track function re-acquires it at the end of the SAM. The ACS communicates this location to the on-board scripts (which needs it to set up the FGS Acquisition and Track functions) and executes the SAM.

With the FGS executing the Track function, the ACS starts receiving 16 Hz guide star centroids. Upon command from the scripts, the ACS will use the guide star centroids and ephemeris to determine the instantaneous pointing error that is to be corrected using the Fine Steering Mirror (FSM).

Modification to the interface between the ACS and the ISIM scripts for supporting observations of moving targets includes new commands to enable and disable "moving target tracking", the transfer of the guide star ephemeris, and a modified SAM request that includes the estimated ISIM overheads associated with the SAM. The ACS must inform the scripts of the updated location of the guide star at the end of the slew (which the ACS has adjusted for the ISIM and ACS overheads to keep the guide star near its ephemeris track).

4 Implementation: Flight Segment

An observation of a moving target with JWST requires the ACS to compensate for the target's motion so that its image remains fixed in the appropriate science instrument aperture while science data are being collected. Just as for observations of fixed targets, an observation of a moving target may require a target acquisition offset to place the target's image within a spectroscopic slit (for example), and dithers to improve angular resolution and/or to provide the means to remove detector artifacts during the post-observation data analysis. These offset maneuvers must also take into account the target's motion across the sky. However, the ACS is not informed of, and therefore does not use the location of a target in a science instrument's aperture to fine point the Observatory. Rather, the ACS uses the location of the *guide star* in the FGS FOV to fine point the Observatory. Thus, to "track" a moving target, the ACS must move the Observatory so that the guide star follows a specific path across the FGS FOV.

The S&OC (see section 5) determines the time-dependent path of a guide star across the FGS FOV that holds a moving target's image at a fixed position in a particular science instrument aperture. This path, here after referred to as the guide star's "ephemeris", is represented in the FGS "Ideal" (distortion-free) Coordinate System (ICS) as a two-dimensional, time-dependent, linear track (although generalization to a polynomial representation may be straightforward and actually simplify operations). This guide star ephemeris is uplinked to the ISIM and provided to the ACS. Offset maneuvers associated with SI target acquisitions and dithers shall be interpreted by the ACS as a SAM, i.e., a delta to the guide star ephemeris.

For a fixed target, the visit file specifies up to three candidate guide stars and their required location on the FGS detector for the initial science exposure. For moving targets, the number of guide star candidates will determined by the length of the visit window (e.g., 1 day) and the angular speed of the target. By having available several guide star candidates with different usability windows, the visit's plan window can be larger than the visit duration, making observations of solar system targets nominally compliant with event-driven operations (**Figure 3-1**).

Each of the candidate guide stars is associated with a usability window and an ephemeris that it is to follow across the FGS. These data are made available to the onboard scripts in an ancillary visit file. At execution time the scripts selects the first usable guide star from this list of candidates. Just as for visits to fixed targets, the scripts will attempt to identify and acquire up to three guide star candidates, if available, to mitigate guide star acquisition failures due to, for example, errors in the guide star catalog.

The actions of the on-board scripts, ACS, and FGS for moving target visits are discussed in the following subsections. In section 4.1 we describe the process beginning with the initial guide star identification & acquisition and ending with the guide star on its ephemeris track in the FGS with science exposures enabled. In section 4.2 we address Target Acquisition, whereby the image of a moving target is to be accurately placed in a science instrument's aperture, such as one of NIRSpec's fixed slits, along with planned offsets (dithers).

4.1.1 Guide Star Identification, Acquisition, & Track

The moving target scenario for identifying a guide star and placing it on its ephemeris track in the FGS is illustrated in **Table 4-1**. The discussion in this section cites the events that are outlined in that table. References are noted as **R1, R2, R3**, for row 1, 2, 3, etc. Coarse Guiding (open-loop) at a fixed attitude is denoted by *fixed-ol.*

Table 4-1 Scenario for moving targets.

	A	B	C	D	E	F
1	Time	Script	ACS	estimated slew size	overheads	OBS Attitude
2	T1	Request Slew to GS ID Attitude	Slew to GS ID Attitude	~90 deg	1 hour	slew
3	T2	Request FGS ID/Acq			75 - 200 sec	fixed -ol
4	T3	**Send GS Ephem (Ps,Ts,dPs) to ACS**	Store GS Ephem for processing			fixed -ol
5			ACS uses GS Ephem to update GS position for SAMs			
6	T4	Request Offset to GS position Ps with **CMD_OVRHD** specified	Calculate GS position at T4 (T4 = time when ACS receives request from AD)			fixed -ol
7			Calculate D_off = predicted offset duration + CMD_OVRHD (including ACQ)			fixed -ol
8			Calculate GS position P5 at T4 + D_off			fixed -ol
9			Perform offset maneuver	~ 1 arcmin	60 sec	SAM
10			Return GS position P5 to AD in SAM complete packet			fixed -ol
11	T5	**Receive GS position P5**			1 sec	fixed -ol
12		Set FGS Acq box, center at GS pos P5			4 sec	fixed -ol
13		Do FGS Acq			15 sec	fixed -ol
14	T5'	Do zero degree SAM with **CMD_OVRHD** specified	Calculate GS position at T5’ (after acq when ACS receives reqest from AD)			fixed -ol
15			Calculate D_off = predicted offset duration + CMD_OVRHD (including time for setting up 32x32 and 8x8 track boxes and transitioning from standby to Track on the 8x8 box)			fixed -ol
16			Calculate GS position P6 at T6 = T5’ + D_off			fixed -ol
17			Perform offset maneuver	< 1"	??	SAM
18			Return GS position P6 to AD in SAM complete packet			fixed -ol
19	T6	**Receive GS position P6**			1 sec	fixed -ol
20		Set FGS Track boxes of 32x32 and 8x8, centered at GS pos P6			4 sec	fixed -ol
21		Command FGS Track with 32x32 box			4 sec	fixed -ol
22		Wait for FGS to signal Track = success			1 sec	fixed -ol
23		Request ACS to Enable Fine Guidance Control (closed loop)	Closed loop tracking with 32x32 track box and using desired GS position P(t) as function of time		1 sec	track
24	T7		Return Fine Guidance Control Enabled flag		1 sec	track
25			Remove GS position error at P(T=now) using 32x32 track box.		~10 sec (assumes 1" pointing error and no CMD_OVRHD margin) & 0.1"/sec rate for FGS	track
26			Once GS is within TBD mas of P6, return Settled flag indicating tracking achieved			
27	T8	Retrieve Fine Guidance Control Settled flag			1 sec	
28		**Request FGS to switch track Box from 32x32 to 8x8 pixels.** ***Note, this is a FSW change for FGS. This is a GO TRACK cmd like for fine lock***	ACS will lose data for 256 - 1024 ms		1 sec	track
29		Receive notification that FGS is using 8x8 window.	Continue closed loop tracking with 8x8 track box and using desired GS position P(t) as function of time		1 sec	track
30		Commence science exposures				track

The S&OC provides the on-board scripts with visit files that contain the necessary information to execute the observations of astronomical targets. For moving targets this includes a list of candidate guide stars, each of which is associated with a usability window and a time-dependent path across the FGS.

A moving target visit commences with the scripts selecting the first usable guide star candidate and requesting a slew (**R2**) to the “identification attitude”, that places the guide star and its associated reference stars in the FGS FOV in such a way as to tolerate coarse pointing errors (8”/axis. 1-σ). With the Observatory attitude held fixed (in coarse guide), the on-board scripts command the FGS to execute the guide star Identification and Acquisition functions (**R3**). The Acquisition function provides the ACS with guide star centroids that can be used to update the spacecraft attitude knowledge.

Following a successful guide star identification and acquisition, the on-board scripts command the ACS to enable “moving target tracking” (**R4**) and provides the ACS with the time-dependent path $P_S(T)$ of the guide star in the FGS FOV, represented as an initial position P_O at time T_O and a rate dP_s, where $P_s = P_o + dPs * (T-T_o)$. P and dP_s are two-dimensional vectors in ICS; with T_o corresponding to a time that is within the guide star's usability window. Using this ephemeris, ACS computes the required location of the guide star in the FGS as a function of time (**R5**) for computing "corrections" to offset requests.

To bring the science target to the appropriate location in the SI FOV, the scripts request the ACS to execute a slew (**R6**) to place the guide star on its "ephemeris" in the FGS FOV. In this request the scripts provide the ACS with an estimate of the "ISIM" time overheads associated with this process, which will include command overheads and the time it will take for the FGS to complete the Acquisition (ACQ) and Track functions at the terminus of the slew. (Note these overheads will be retrieved from a lookup table.) To these overheads the ACS adds (**R7**) an estimate of the time it takes to slew and settle at the desired attitude (this estimate includes the elimination of the pointing error that is inferred from ACQ guide star centroids at the ID location). Using these combined overheads, the ACS computes (**R8**) the location of the guide star along its ephemeris at the projected time $\mathbf{T_5}$ when the FGS is complete the ACQ and Track functions. The ACS executes the slew to place the guide star at desired location (**R9**) and subsequently informs the scripts of this position via telemetry (**R10**).

Upon acknowledgement from the ACS that the maneuver has completed, the on-board scripts command the FGS to execute the ACQ function (**R12, R13**) at the predicted location of the guide star (which had just been provided by the ACS). While the FGS executes the ACQ function, the ACS holds the Observatory at a fixed pointing, just as it does for visits to fixed targets. The FGS computes the guide star centroids that are used by the ACS to update the attitude knowledge (or equivalently, to measure the pointing error).

Upon completion of the ACQ function, the scripts commands the FGS to Standby and requests the ACS to perform a "zero degree" SAM (**R14**) to remove residual pointing errors from the previous maneuver. This command includes an estimate of the overhead (from commands and setup time) associated with the time it takes for the FGS to begin execution of the Track function with the 8x8 pixel sub array at the end of the SAM (predicted time T5'). As before, the ACS adds this "updated" ISIM overhead to its own estimate of the time to slew and settle (**R15**) and computes (**R16**) the guide star's position ($\mathbf{P_6}$) along its track at that time. The ACS executes the SAM (**R17**) and informs the scripts of the guide star's expected location $\mathbf{P_6}$ in the FGS FOV (**R18**) in the "SAM complete telemetry packet".

Upon notification by the ACS that the SAM has completed, and with the Observatory held at a fixed pointing, the scripts command the FGS (**R21**) to execute the Track function at the predicted location ($\mathbf{P_6}$) of the guide star's image. For a visit to a fixed target, this command group instructs the FGS to setup a 32x32 pixel sub array for the Track function, and to prepare the setup for an 8x8 pixel sub array to be used subsequently for the Fine Guide function. (This enables a rapid transition from Track to Fine Guide with a minimal gap in guide star centroid telemetry). However, for moving target visits, the scripts instruct the FGS to use both the 32x32 and the 8x8 pixel sub arrays for the Track function, and to begin using the 32x32 pixel sub array.

Upon receipt from the FGS FSW that the Track function has succeeded using the 32x32 pixel sub array (**R22**), the ISIM on-board scripts command the ACS to commence closed loop guiding

(**R23**) to drive the Guide Star to the fixed position P6, using (for the first time in this process) the 16 Hz guide star centroids to eliminate the pointing error at the end of the just-completed SAM. ACS informs the ISIM that the Fine Guidance control loop has been closed by setting the "*Fine Guidance Control Enabled*" flag (**R24**).

The ACS informs the ISIM when the guide star has been brought within TBD milli-arcsec of P6 by setting the "*Fine Guidance Control Settled*" flag (**R26**). Then the on-board scripts command the FGS to transition to the 8x8 pixel sub array (**R28**). During the transition there will be drop out of 256 to 1024 milliseconds of valid guide star centroids. The FGS FSW notifies the on-board scripts when it has successfully transitioned to the 8x8 pixel sub array (**R29**), and the ACS begins to using the moving guide star ephemeris evaluated at 16 Hz and the FGS centroids received at 16 Hz to determine the instantaneous pointing error that is to be corrected. This is a prerequisite for the scripts to commence (**R30**) observations of the moving target with a science instrument.

4.1.2 Target Acquisition & Dithers

Observations of a solar system object that require its image to be accurately placed in a small aperture, such as one of NIRSpec's fixed slits, will require a target acquisition procedure. Employing the concept that has been developed for target acquisition of fixed targets (JWST-STScI-000961, "JWST Science Instrument Target Acquisition: Use Cases, Flight Software Requirements, and Verification Plans"), the moving target will be imaged by the appropriate science instrument (using a sub array) while the ACS maintains the guide star on its ephemeris in the FGS (i.e., JWST tracks the science target). The image data are analyzed by the ISIM to determine the target's precise location on the instrument's FOV, from which the offset to the science aperture is computed. The on-board scripts request the ACS to execute this offset, which the ACS will interpret as an offset to be applied to the guide star's ephemeris.

Observations of Solar System objects may include planned dither patterns as part of the visit. Just as for observations of fixed targets, dithering can improve the angular resolution of a processed image (by sub pixel sampling of the PSF), and can be helpful in removing detector artifacts during post-observation data analysis. A typical visit may have multiple dithers. To execute a given dither, the ACS sums the current offset request with all of the preceding dithers (and the target acquisition maneuver, if applicable) to compute the effective offset to be applied to the guide star's ephemeris for the current SAM, as illustrated in **Figure 4-1**.

Table **4-2** chronicles the interaction between the on-board scripts, FGS, and the ACS for the target acquisition scenario.

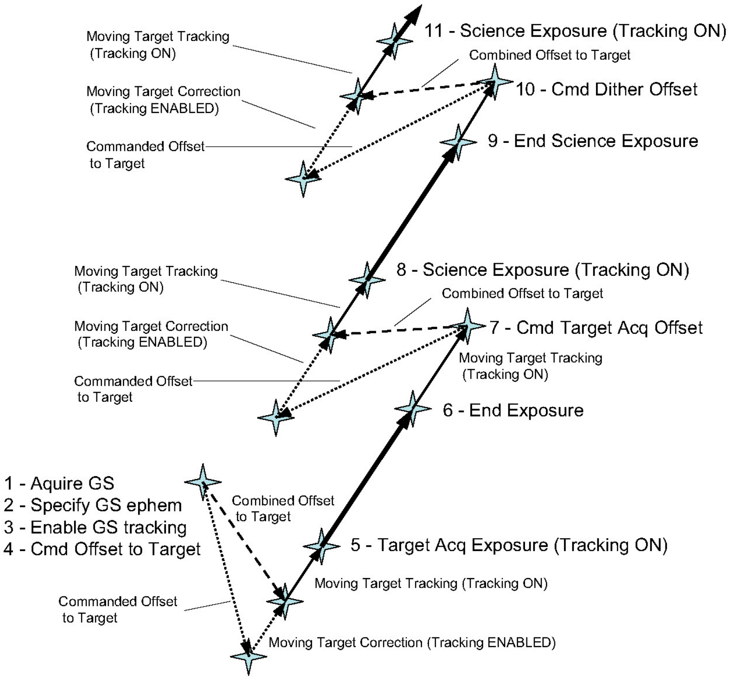

Figure 4-1 Moving target offset scenario. The individual maneuvers accumulate as offsets to the guide star's ephemeris track.

Table 4-2 Target acquisition scenario for moving targets.

	A	B	C	D	E	F
1	Time	Script	ACS	estimated slew size	overheads	OBS Attitude
31						
32		**Execute target acquisition exposure**				track
33		Calculate target acquisition offset		up to 40" (MIRI IFU)		track
34	T9	Instruct ACS to disable Fine Guidance Control	Stop tracking, stop updating GS position as a function of time		1 sec	fixed -ol
35		Set FGS to standby			1 sec	fixed -ol
36	T10	Request TA Offset with **CMD_OVRHD**	Calculate GS position at T10			fixed -ol
37			Calculate D_OFF = predicted offset duration + all command overheads			fixed -ol
38			Calculate GS position at T11 = T10 + D_off			fixed -ol
39			Perform offset maneuver	0 to 40"	1 to TBD seconds	SAM
40			Return GS position P11			fixed -ol
41			Calculate GS position P(t) as func of time			fixed -ol
42	T11	Receive GS position P11				fixed -ol
43		Command FGS to Acquisition Mode (line 12-21)				fixed -ol
44		Set FGS Track Box, center at GS pos P10				
45		Proceed as in lines 22 to 31.				track
46						
47		**Execute Planned dither**				track
48		Retrieve Dither offset		up to 20" (NIRSpec)		track
49	T12	Instruct ACS to disable Fine Guidance Control	Stop tracking, stop updating GS position as a function of time		1 sec	fixed -ol
50		Set FGS to standby			1 sec	fixed -ol
51	T13	Request Dither Offset with *MT Tracking* enabled	Calculate GS position at T13			fixed -ol
52			Calculate D_OFF = predicted offset duration + all command overheads			fixed -ol
53			Calculate GS position at T14 = T13 + D_off			fixed -ol
54			Perform offset maneuver	0 to 20"	1 to TBD seconds	SAM
55			Return GS position P14			fixed -ol
56			Calculate GS position P(t) as func of time			fixed -ol
57	T14	**Receive GS position P14**				fixed -ol
58		Set FGS Track Box, center at GS pos P14				fixed -ol
59		Proceed as in lines 22 to 31.				track
60						

As shown in
Table **4-2**, the target acquisition scenario begins with the science instrument executing its target acquisition procedure (**R34**) and the ISIM computing the necessary offset of the target in the science instrument's FOV (**R35**). The subsequent interactions (rows **39** to **64**) between the on-board scripts, FGS, and ACS follow that same scenario as for the maneuver from the guide star identification and acquisition attitude to the science attitude shown in
Table **4-2** (rows **6** to **32**). The only exception is that the ACS computes the "effective" commanded position of the guide star by applying the target acquisition SAM as an offset to the guide star ephemeris that was provided by the on-board scripts.

Dithers follow the same scenario as target acquisition, with the only difference being that the offsets for the SAMs are specified in the visit file.

5 Implementation: Ground Segment

This section specifies a ground segment operations scenario for observations of Solar System targets with JWST. This includes proposal preparation, planning, scheduling, execution, and data archiving. The assumptions around which this scenario has been built are itemized below. 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 scenario 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 efficiently 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 and Solar System objects' ephemerides are known with sufficient accuracy to allow for the preliminary selection of guide stars several months in advance of the date of observation.
(5) A potentially large set of guide star candidates will be selected for the visit, each with its own usability window, set of reference stars, acquisition attitude, and ephemeris track in the associated FGS channel. However, only one guide star, if successfully acquired, will be used for the duration of the visit. (i.e., guide star "handoffs" are not part of the scenario).

A high level overview of the ground system architecture for proposal preparation, planning and scheduling is shown in Figure 5-1. Unique to moving target proposals is the need to access the JWST ephemeris and target ephemeris to determine the track and usability windows for the candidate guide stars.

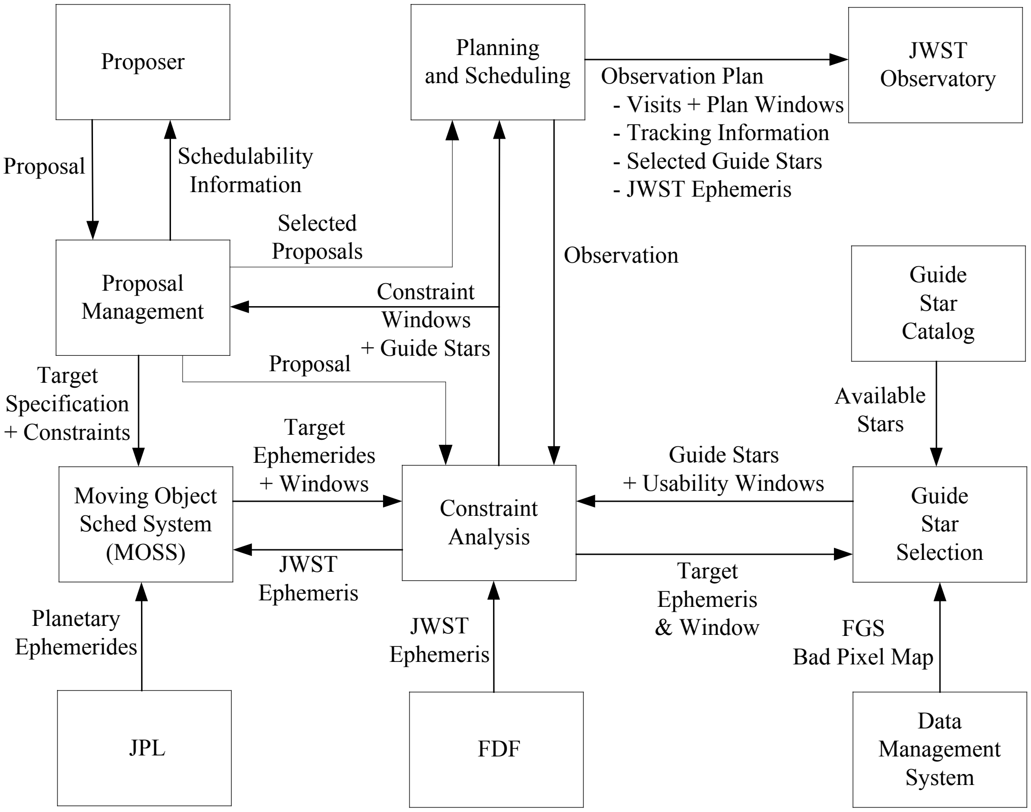

Figure 5-1 Proposal preparation, planning, & scheduling system for moving targets.

5.1.1 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 that must be met to achieve the observer's scientific objectives. For fixed targets this will include the object's position and proper motion, its spectral colors and magnitudes, its clasification 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 (via JPL) will provide the ephemeris of all standard objects. The observer will specify the orbital elements for non-standard objects.

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. 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 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 preliminary 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.

5.1.2 Proposal Planning and Scheduling

The Proposal Planning & Scheduling System (PPS) residing at the S&OC will accept and process a standard proposal (built using S&OC-provided templates) from an observer. For fixed targets, the object's position will be specified by its coordinates in a standard reference frame (ICRS). For moving targets, the S&OC will access either an ephemeris for "standard" solar system targets, or accept the orbital elements for non-standard targets, such as a KBO, provided by the observer. For scheduling, all constraints applied to observations of fixed targets will remain valid, plus the requirement that guide stars with usability windows that are longer than the visit are available. 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 scheduling paradigm, the visit may execute any time within the planning window. The PPS 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 (using MOSS). Using the ephemeris of the target to determine the time-dependent attitude of the Observatory while JWST observes the target, the scheduling system queries the guide star catalog (GSC-2) to select guide star candidates that remain in the FOV while avoiding bad regions (e.g., clusters of bad pixels) of an FGS channel for a time that is longer than the visit's maximum length. For each selected guide star, the PPS selects reference stars for the identification phase of the guide star's acquisition, determines an "ephemeris" the guide star is to follow across the FOV of the appropriate FGS channel to keep the science target at a fixed location in the science instrument aperture, and the usability window of the guide star.

Vist windows will be made as large as possible, up to one day long, to take advantage JWST's event-driven operations to achieve maximum observing efficiency. To support this objective for moving targets, PPS will provide a list of guide star candidates, each with its own usability window, that collectively span a visit wndow which, barring any target specific constraints, is up to one day long. This list, along with the necessary ancillary data, will be provided to the on-board scripts, which will select up to three candidates (to provide tolerance against acquisition failure) with usability windows appropriate for the time the vist actually executes.

6 Requirements

To accurately determine the scope of the work required to implement the moving target tracking capability, the affected requirements needed to be identified as there will be some effort required to process the changes required to implement the capability to track moving targets. While not a large portion of the effort, it is not insignificant given the current level of maturity of the requirements and the number of signatories to many of the documents. We have provided an initial cut at the top level requirements to bound the effort, and have attempted to identify all affected documents, but a requirements analysis will be necessary to ensure full compliance. In all cases, the requirements are verified by analysis or simulation as described in section 7, the Verification Plan. In most cases the MT tracking capability is verified in parallel with the FT tracking requirements.

6.1.1 Top level requirements

6.1.2 Existing requirements

In the Science Requirements Document, JWST-RQMT-002558, rev. A:

> **8.18 Moving Object Tracking**
> SR-31 When requested the Observatory shall track targets which exhibit any angular velocity in the range of 30 mas/s over a total motion 30 arcsec with respect to the guide star (**TBR**).

In the Mission Requirements Document, JWST-RQMT-000634, rev N:

> **3.7.1.7.5 Image Quality for Moving Targets**
> This section delineates the list of optical requirements that shall be met when tracking moving targets. Unless specified in this section, all other optical requirements do not apply to moving targets. The optical requirement MR-371 shall be met when tracking moving targets.
>
> **3.7.1.7.5.1 Strehl Ratio For Moving Targets**
> MR-371 Over the FOV of the NIRCam, the Observatory shall be diffraction limited at 2 μm defined as having a Strehl Ratio greater than or equal to (To Be Determined [**TBD**]) when tracking any available target that exhibits an angular velocity v in the range of (**TBD**) milliseconds of arc per second (mas s^{-1}) with respect to the guide star.
>
> **3.7.1.13.3 Moving Target Tracking**
> MR-372 When commanded the Observatory shall track targets which exhibit any angular velocity in the range of (**TBD**) milli-arseconds per second over a total motion (**TBD**) arcsec with respect to the guide star.

6.1.3 Proposed new and revised requirements

This study showed that an angular velocity of 3 mas/s and a total motion of up to 2 arcminutes with respect to the guide star is feasible provided the image quality only needs to be maintained for a single integration time of <1000 seconds. This is due to being able to use a single guide star over the FGS-Guider field of view for any given observation. We propose to modify MR-371 and MR-372 to be consistent with the requirements of the study. We also propose to add an additional requirement addressing the absolute pointing accuracy, with the values currently TBD. We will propose wording for the requirements updates after project approval of moving target tracking.

In addition, Observatory specifications will have to be flowed down from these into sections 3.2 and 3.7 for both the ISIM and the OTE/SV elements, and from there down to the lower level specifications.

6.1.4 Expected affected documents

Many documents are affected which will require Systems Engineering to generate requirements and requirements flow down, in addition to verification plans. The documents listed here will likely need updating to include Moving Target Tracking capability for the JWST. Additional lower level documents will also need updating as the requirements flow down through the system. In addition, some other documents may be affected that have not been identified during this study, but will be updated as part of normal engineering practices.

JWST Mission Requirements Document, JWST-RQMT-000634
JWST Observatory Specification, JWST-SPEC-002020 (SY1-0100)
JWST Mission Operations Concept Document, JWST-OPS-00218
JWST Ground Segment Requirements Document, JWST-RQMT-001056
ISIM Requirements Document, JWST-RQMT-000835
ISIM to OTE and Spacecraft IRCD, JWST-IRCD-000640 (IF31-0080)
Spacecraft Requirements Document, JWST-RQMT-002039 (SY1-0101)

6.1.5 Expected new commands

Our analysis identified only six new or modified onboard commands**:**

1. The onboard scripts send the GS ephem (Ps, dPs, Ts) to ACS
2. The onboard scripts send an estimate of command overhead time to ACS
3. ACS sends the computed GS position P at future time T to the onboard scripts
4. The onboard scripts request FGS to set an 8x8 Track box
5. The onboard scripts request ACS to begin tracking the moving GS ephemeris
6. The onboard scripts request ACS to stop tracking moving GS ephemeris

The ACS must add capability to evaluate the moving GS ephemeris.

The only new requirement on the FGS is that it accept and act on a new command to set an 8x8 Track box. This is almost identical to the existing command to set an 8x8 Fine Guide box for fixed targets.

Further refinement of the onboard procedures may identify more required commands, but it is highly unlikely that any other capabilities will be required of the FGS.

6.1.6 Performance error budget

To evaluate the performance of the observatory when tracking moving targets, a modified pointing error budget was developed that includes the impacts of tracking a moving target with the observatory. The key differences are the FGS noise equivalent angle (NEA) (increased to 6 mas from 4 mas for a fixed target case based on requirement FGS SRD 171 for up to 30 mas/s motion), an increase in the SV disturbance levels by 20% due to motion of the observatory, an increase in the FSM smear due to the update rates, an error due to the clock error (which will depend on the total integration time and when the update is applied), and an error caused by the absolute roll error resulting in an error in the motion compensation direction. In addition, an estimate of the error due to ephemeris errors for the target is carried at the top level which can be partly accommodated by the available margin.

The resulting error budget showed that the 50 mas (3σ) pointing budget could be met rather easily. At a moving target rate of 3 mas/sec, about half (in the RSS sense) of the 50 mas was contributed by spacecraft motion and guidance errors, and about half could be retained as margin. The errors in the moving target ephemeris representation and computation contributed less than 3 mas for a relatively well characterized object which has a minimal impact to the pointing stability. The margin is somewhat less for a moving target rate of 30 mas/sec, but the 50 mas target accuracy is attainable at that rate using these assumptions.

7 Verification

All performance requirements will be verified using high fidelity simulations. Functional and interface requirements will be verified in the SDL and then validated in the EMTB.

7.1.1

7.1.2 SV components

The space components will first be tested in the ACS high fidelity simulator. This will test the performance of the moving target tracking in using high fidelity models of the ACS sensors and actuators, FGS, FSM, and sampling characteristics.

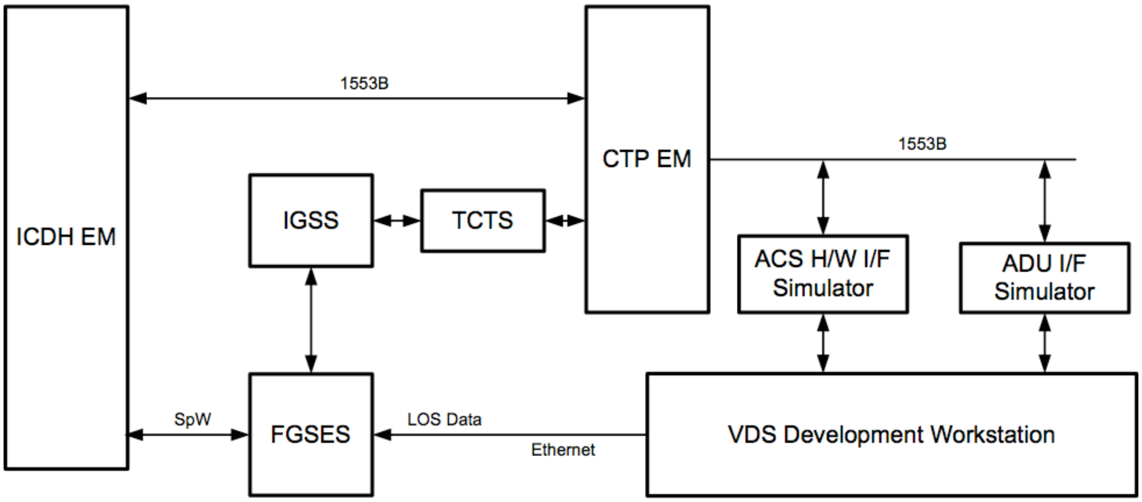

Figure 7-1 Engineering Model Test Bed (EMTB)

7.1.3 Ground components

There will be additional test cases in the S&OC System for moving target tracking. These will be documented in the S&OC System Test Plan (SM-07), Test Procedures (SM-08) and Test Report (SM-09).

Test cases for moving target tracking will also be added to in the Ground Segment testing. These will be documented in the Ground Segment Test Plan (SV-01), Test Procedures (SV-02) and Test Report (SV-03).

Additional analysis will need to be performed to verify moving target requirements. This is documented in the in the End-to-End Data Flow Test Plan (SV-04), Test Procedures (SV-05) and Test Report (SV-06). System Engineering support is needed to support these analyses.

7.1.4 Interfaces

The on-board scripts interface to the FGS and SC will be tested in ISIM Flight Software Lab using the FGS electrical simulator (FGSES) and the SC simulator (SCSim).

The interfaces and the functionality of the Capability will also be tested in the Engineering Model Test bed (EMTB) (Figure 7-1). This will check the command and telemetry interfaces between the IC&DH, ADU, and CTP.