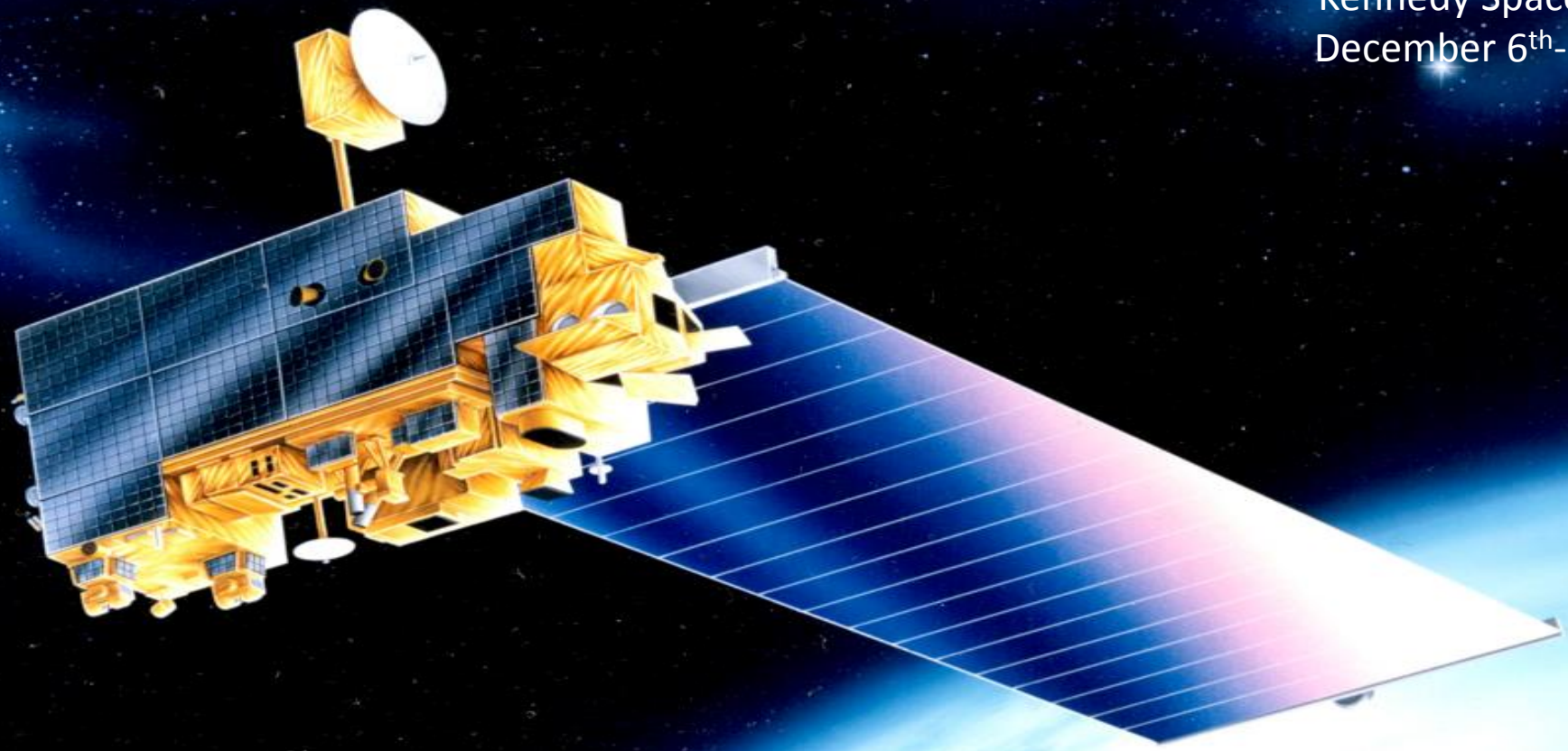
EOS Terra

EOS DAM Automation Constellation MOWG

Kennedy Space Center
December 6th-8th, 2017



Dimitrios Mantziaras
Terra Mission Director - Code 428
phone 301-614-5234
Dimitrios.C.Mantziaras@nasa.gov

ESMO's DAM Planning Automation

- **ESMO updated its Close Approach (CA) Process Flow to a more Automated approach**
  - Prepares for future increased object catalog w/ Space Fence
  - Reduces workload for each event
  - Keeps solution "at the ready" for short notice events
- **ESMO Flight Dynamics team has developed an autonomous ephem generation tool**
- **Ephems built off optimal and constrained cases solved for by the Collision Risk Management System (CRMS)**
- **CARA accepts delivery of these ephems and ships them to JSpOC for screening**
  - Delivery to CARA will be automatic based on logic built into the FDS ephem tool
- **Screening results automatically compiled and reported via email from CRMS**
- **Auto Ephem Generation implemented on February 13th, 2017**
- **Auto Ephem Delivery scheduled for December 2017**

How Did We Get There?

Agenda

- High Level Aspects of CA Process
- Orbital Constraints
- Notification Timelines
- Process Improvements
- Future Plans & Challenges
- Backup Slides

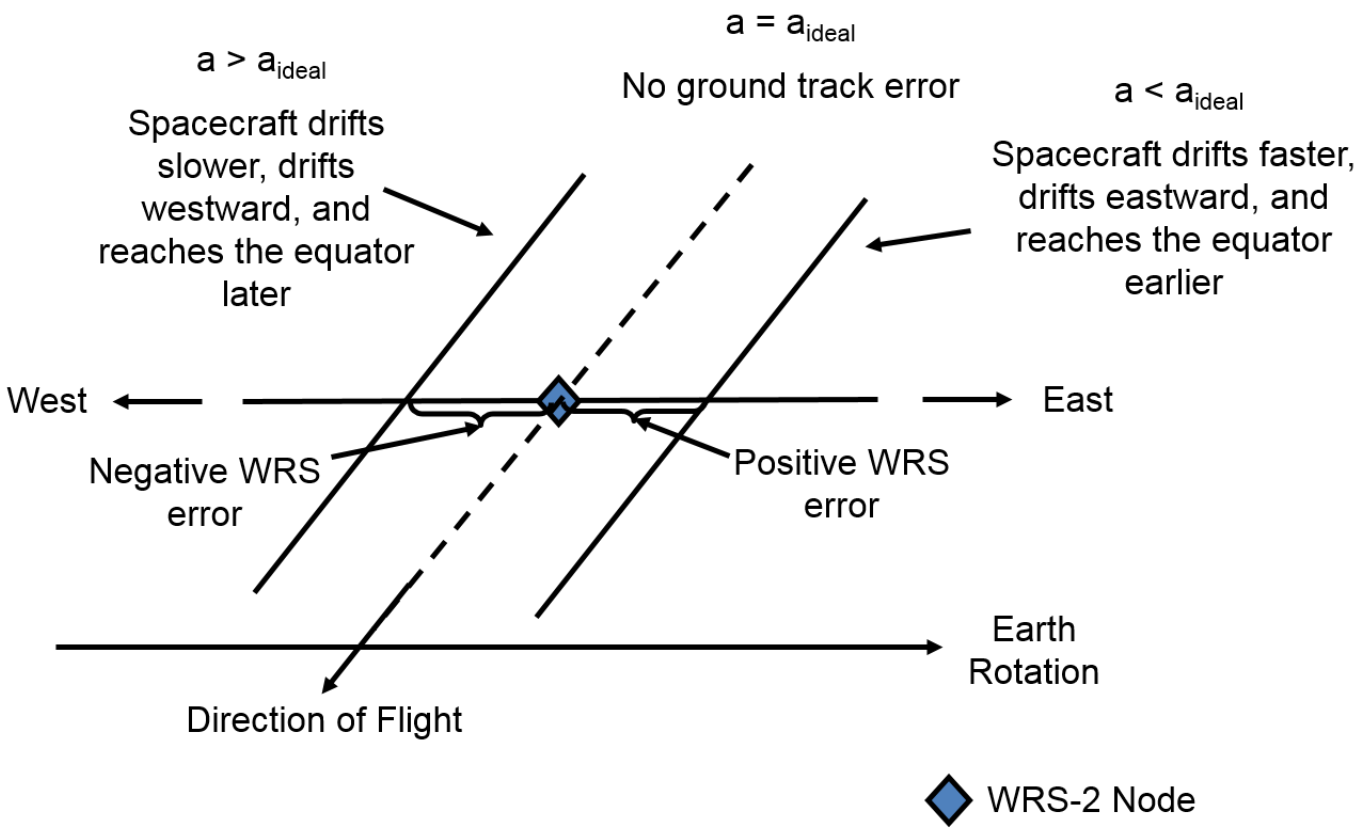
High Level Aspects of CA Process

Mission Director's Perspective

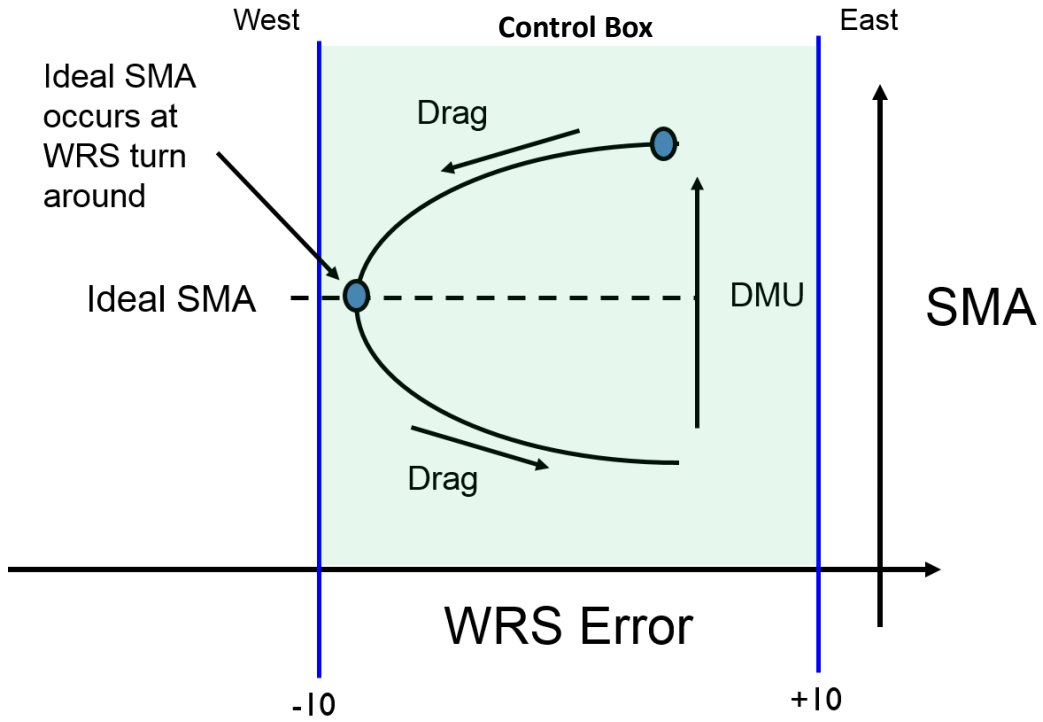
- **Sensor data from JSpOC** — **Information Source**
  - Routine Screenings
  - Tasking Prioritization
- **Data Analysis** — **Information Source**
  - Understanding confidence in solution
  - Assessing risk
  - Identifying burn times & duration
- **Maneuver Planning** — **Readiness for Action**
  - Contact Scheduling
  - Product Generation & Delivery
    - Ephems & Planning Aids
  - Coordination with Instrument Operations Team
  - Identifying options within mission/science constraints
- **Maneuver Execution** — **Decision for Action**
  - Use propulsion system to impart delta-v on spacecraft
  - Returning to nominal science data collection state

Decision Factors: EOS Mission Orbit Constraints

Top View



Side View



- EOS Missions fly 705 km, Sun-synchronous polar 16 day repeat orbits @ 98.2° Inclination
- Mission Science goals dictate orbital maintenance requirements including **ground track** (Inclination & DMUs)
- EOS Missions fly in constellations, therefore must fly inside their **control box** (orbital safety & science)

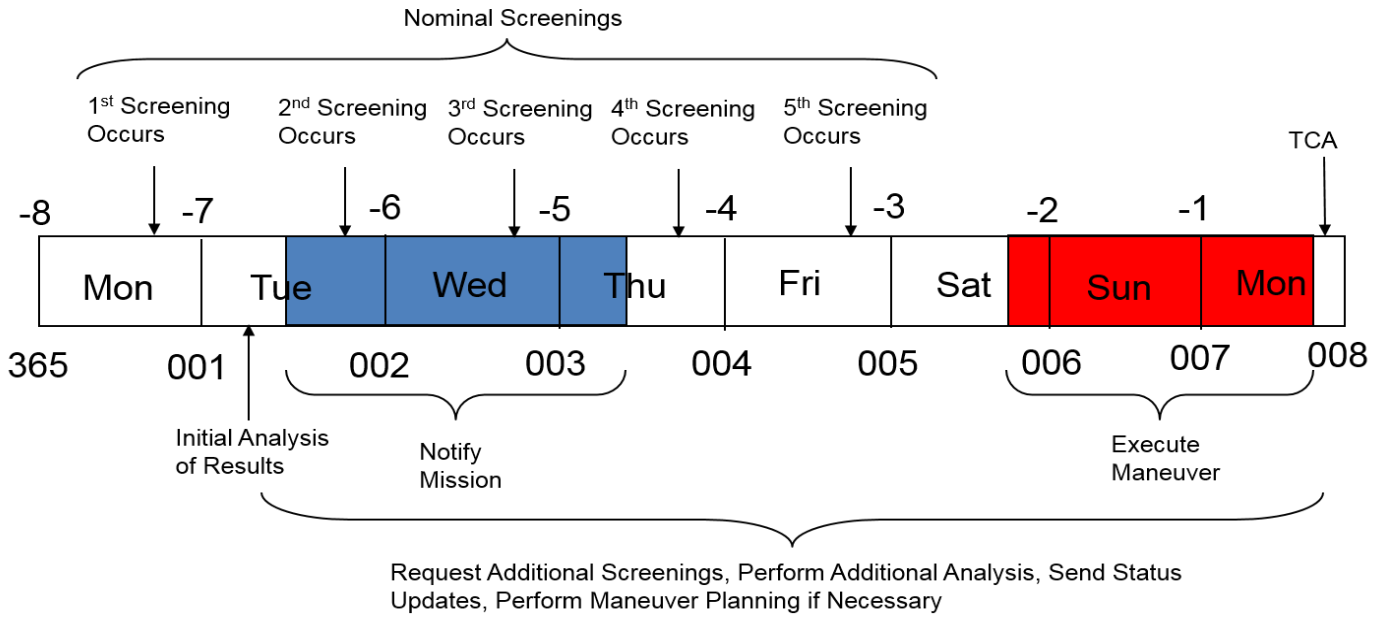
Source: EOS Flight Dynamics, 2016

Decision Factors: Spacecraft Design/Constraints

- **EOS Missions fly in repeat ground track orbits at 705km**
- **Spacecraft designed to perform Drag Make-Up (DMU) and Inclination Maneuvers**
  - Retrograde capability not part of nominal maneuver set
- **Drag Make-Up Maneuvers therefore used as Debris Avoidance Maneuver (DAM) to mitigate debris risk**
  - Raise altitude (can only go up, one direction)
- **Differences in DMU & Debris Avoidance Maneuver (DAM) concepts are significant**

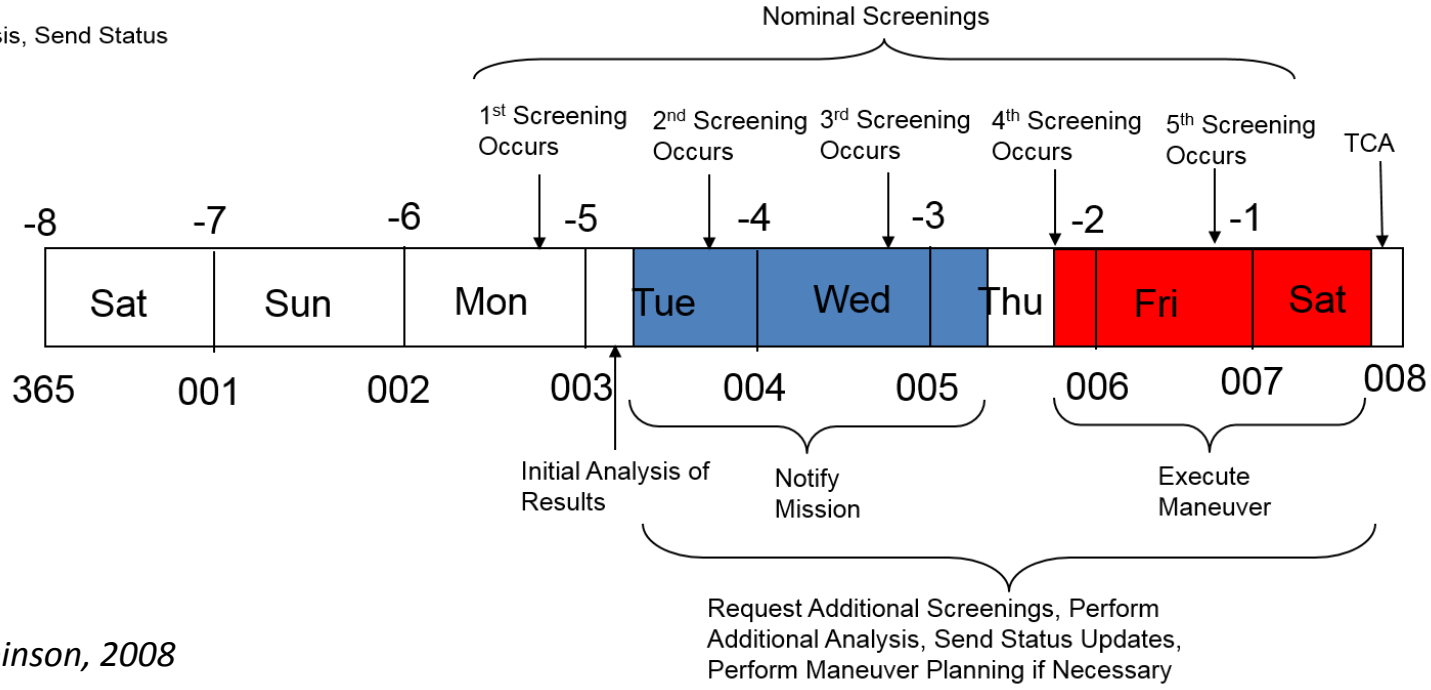
	DMU	DAM
Purpose	Maintain Orbit Altitude	Avoid Debris
Notification Time	Several Weeks	Few Days or Less
Ops Mentality	Routine, Methodical	Urgent, Quick Turnaround
Contingency Action	Reschedule	Health & Safety Concern
Burn Duration	Well Defined	Variable
Burn Options	One	Multiple
Execution Time	Day Shift Only, M-F	Anytime, Any Day

Decision Factors: Generic Timeline Scenarios (2008)



Well Tracked, Early Notice Secondary Object
(Stable Pc)

Poorly Tracked, Late Notice Secondary Object
(Variable Pc)

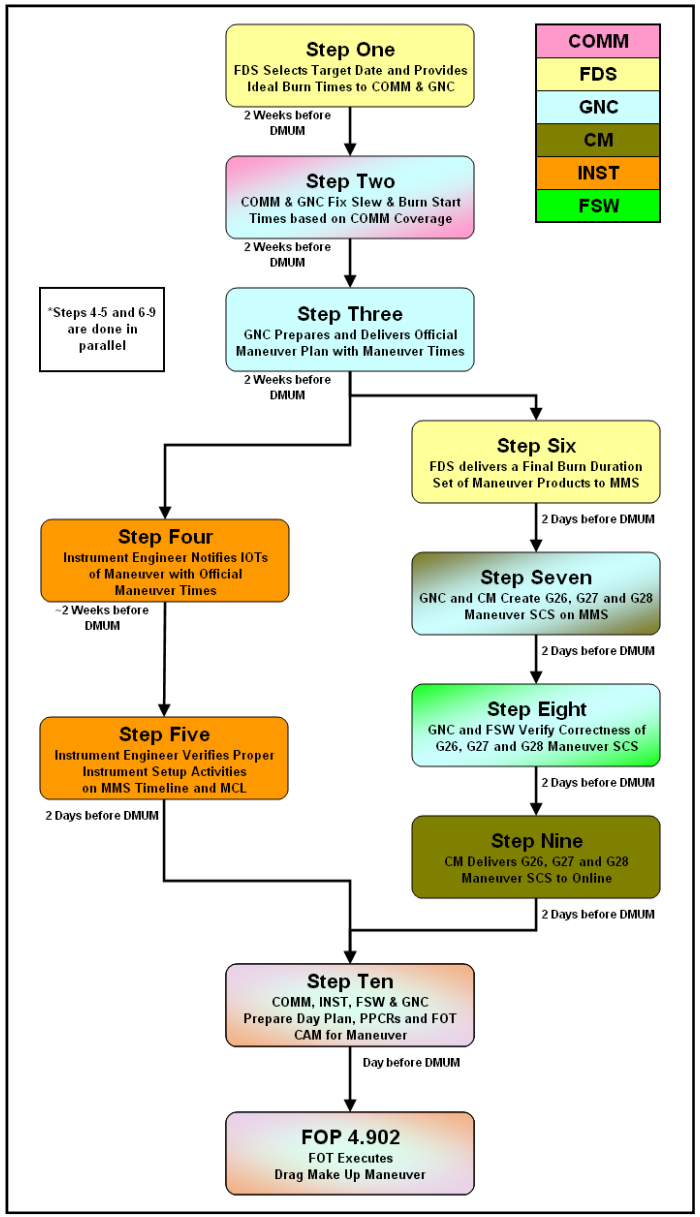


Source: Brian Robinson, 2008

Process Improvement: Maneuver Execution

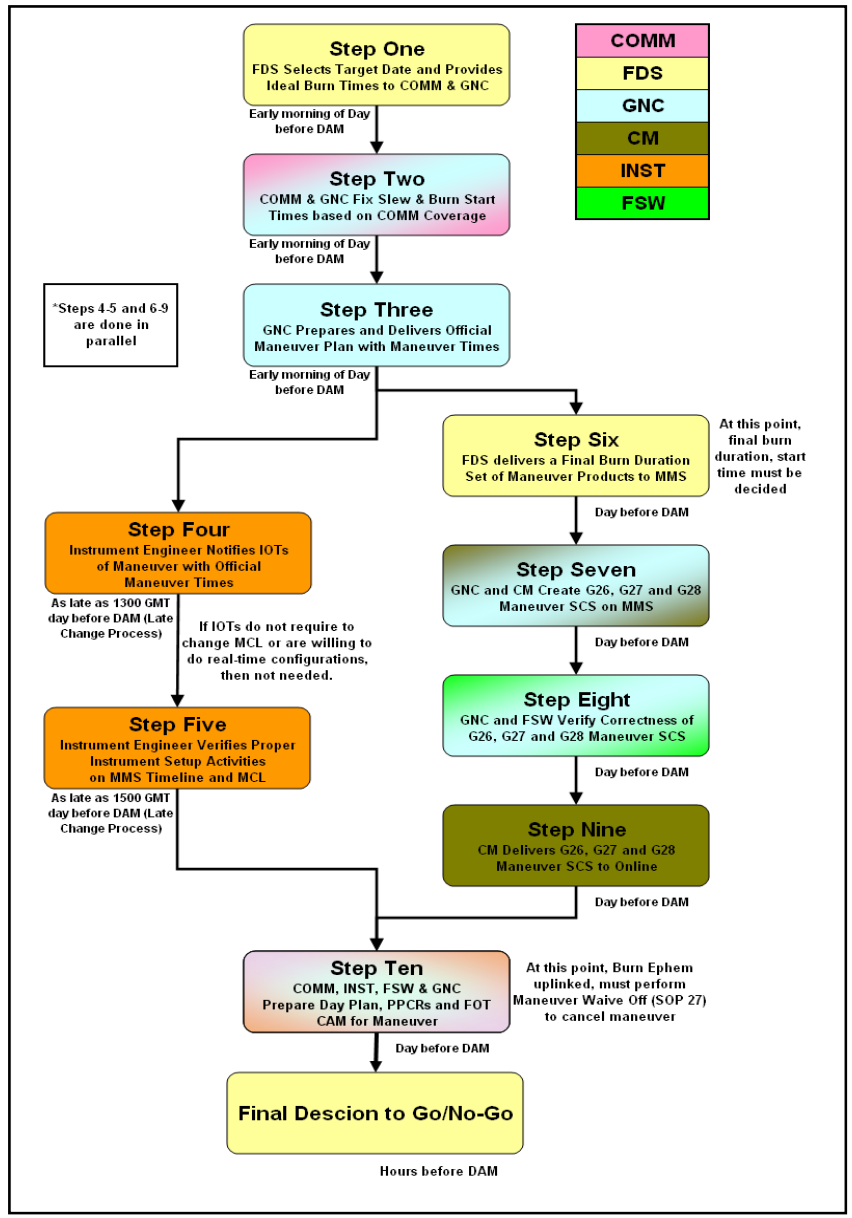
Original DMU Timing

- Process started **~2 weeks** before maneuver
- Main prep activities **~2-3 days** prior to maneuver
- **Multiple** personnel required
- **Reliant on stored commands**



Accelerated DAM Timing

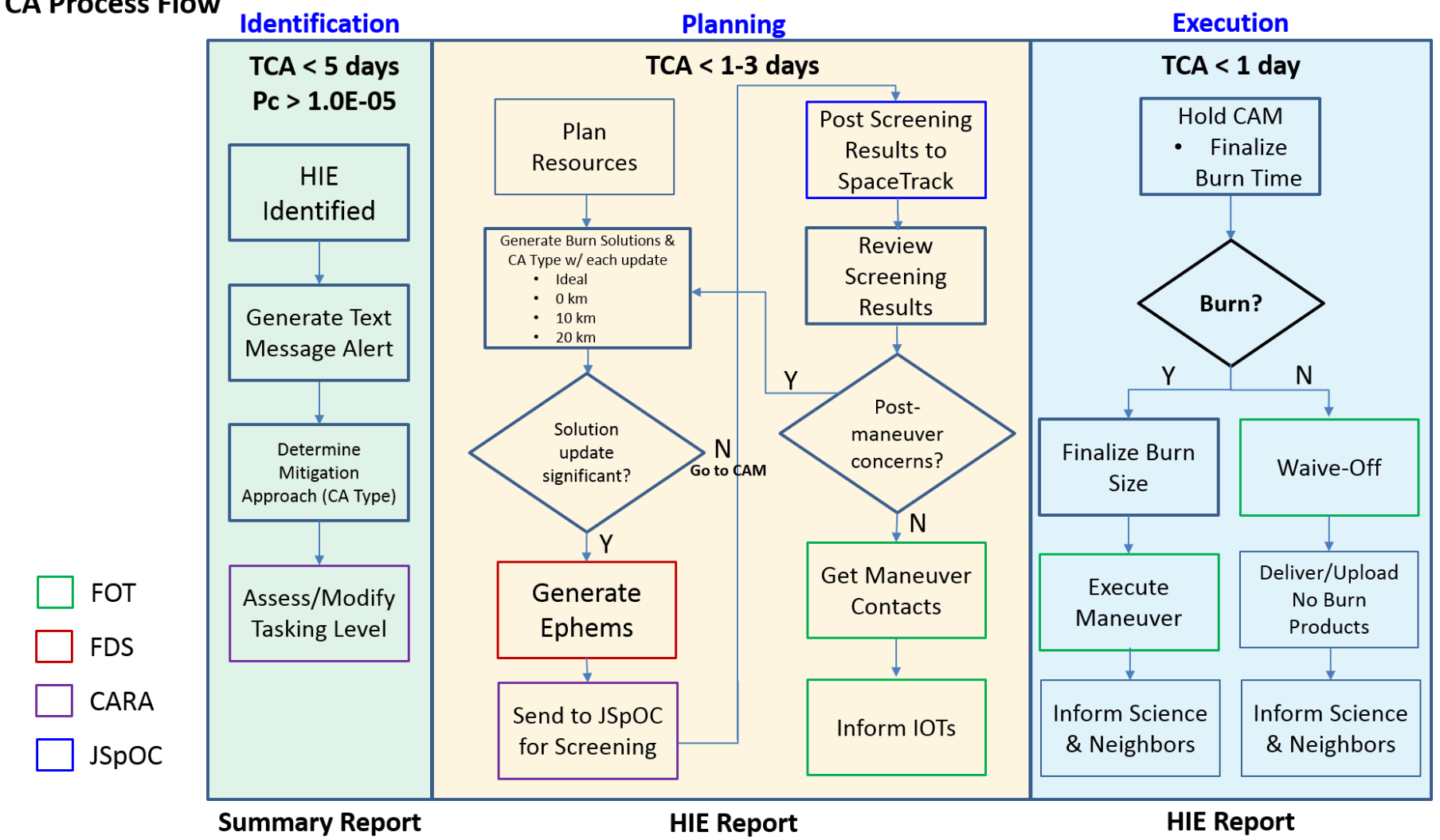
- Process shortened to begin the **day before** the maneuver
- Main prep activities **1 day prior** to maneuver
- **Reduced personnel required**
- **Reliant on stored commands**



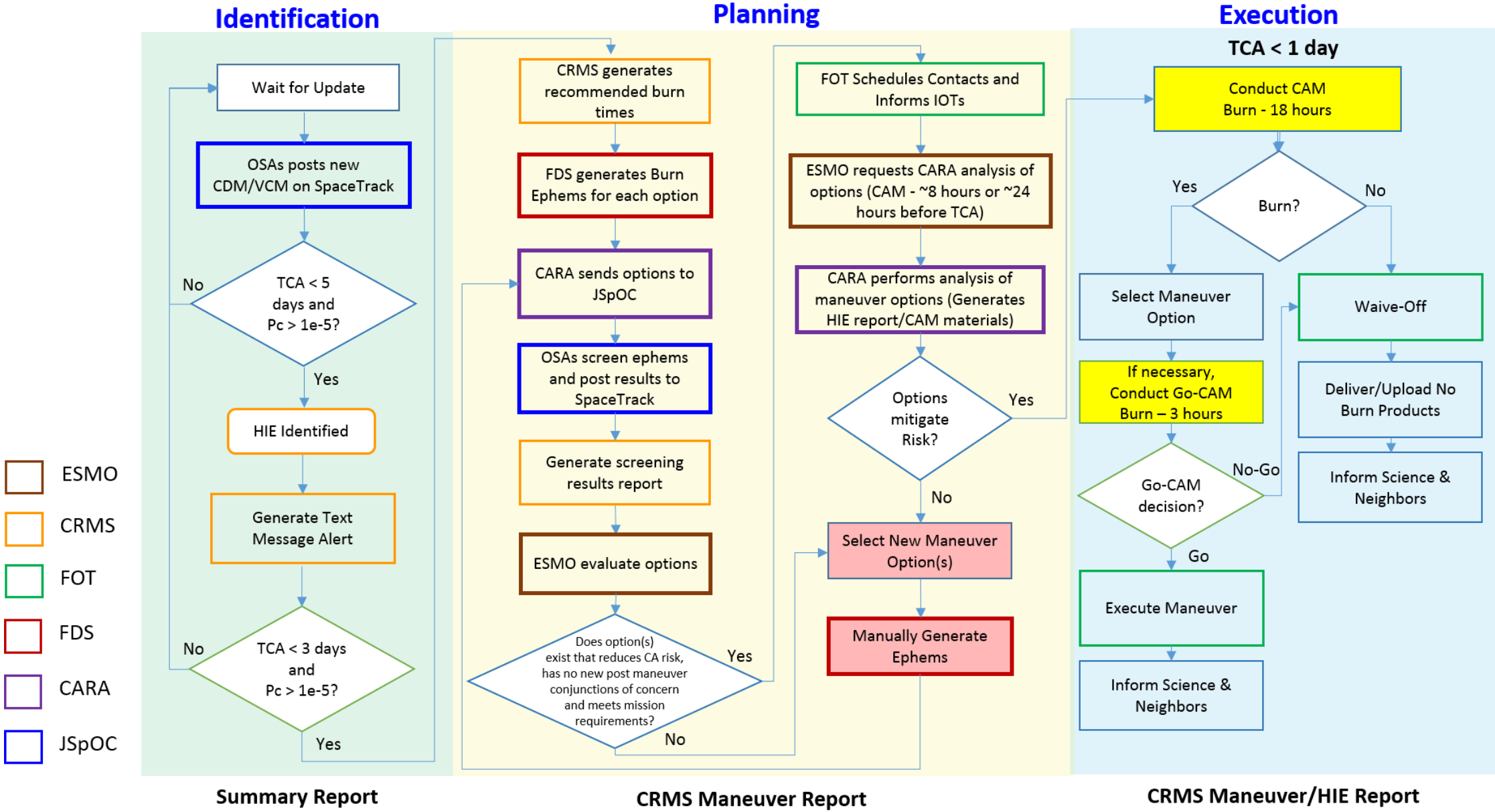
Process Improvement: Document Overall Process

- Reviewed Overall Process with Mission Stakeholders
- Documented the Overall CA Process in the Mission Director Handbook

CA Process Flow



Process Improvement: Updated ESMO CA Process Flow (2016)



Process Improvement: Define Risk Thresholds at Decision Point

EOS Maneuver Thresholds for DAM/No-DAM

	Pc Thresholds	Odds Range	Course of Action	Sample Scenarios
Green	**$<1.0e^{-5}$**	1:100,000 to 0	**No DAM**	
Yellow	**($1.0e^{-4}$-$1.0e^{-5}$)**	1:10,000 to 1:100,000	**Altered DMU/No DAM**	Replan Nominal DMU burn time or execute DMU early <u>if available</u> For well-tracked objects with small miss distances
Orange	**($1.0e^{-3}$-$1.0e^{-4}$)**	1:1,000 to 1:10,000	**DAM**	Solution <u>within</u> mission/science requirements and low uncertainties
Red	**($1.0e^{-2}$-$1.0e^{-3}$)**	1:100 to 1:1,000	**DAM**	Execute even if <u>outside</u> mission/science requirements
Black	**$\geq 1.0e^{-2}$**	1:1 to 1:100	**DAM**	**Maneuver at all costs** Even if Ongoing Anomaly (Non-Maneuver Component)

- All unacceptable risks are mitigated
- Additional risks are mitigated within mission/science constraints
- Confidence in OD solution/risk accuracy must be considered as well

Process Improvement: Define Data Needed

Info Needed for All Objects (Each Update)

- Days to TCA
- TCA
- Secondary Object Name & Catalog Number
- Primary Object Ephem Source (ASW or O/O)
- Screening Epoch
- Total Miss Distance (m)
- Miss Components (R, I, C – meters)
- Pc (single object & aggregate for mission)
  - Color coded to visual help identify risk categories
    - Red, Yellow, Green, Orange & Black
    - Thresholds for each category set by ESMO by Mission
- Indication if New Track received on Secondary
- Relative Velocity/Approach Angle
- Indication if Active Mission

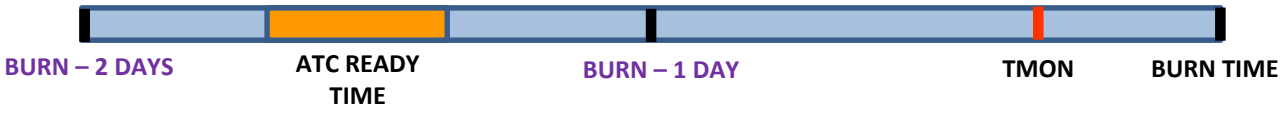
- Missions should define what information they need to make an informed decision
- Basic info for all objects in monitor volume versus more details for high risk objects

Additional Info Needed for High Interest Objects

- Repeat of summary info for object in question (info on left)
- Plots of Total Miss History, Pc history, Component Uncertainty History
  - Indicate which data points contained a new track
- Ephem name used for O/O solution
- Event Geometry (in table form – both ASW and O/O columns)
  - Component Uncertainties
  - Relative Velocity
  - Approach Angle
- Secondary OD info
  - **Orbital Parameter** (Period, Perigee Height, Apogee Height, Inclination, EDR & RCS)
  - Avg. Observations per day
  - OD Fit Span (days)
  - Time Since Last Observation
  - Total Propagation Time (days)
  - Orbital Parameter & Event Flag Info
  - Space Weather Info
  - How well behaved is the secondary object??
- Maneuver Trade Space Plots
  - Combined, Secondary, Post-Maneuver Objects of Concern
  - Timeframe of MTS plot would be dictated by Event Type/Mitigation Approach
  - Delta-V or Burn Duration to stay within Mission/Science Control Box
- Optimized Maneuver Solution(s)
  - Targeted probability for maneuver solution mitigating risk

Process Improvement: Maneuver Execution Enhancement

- **Needed to remove reliance on Stored Commands (ATC)**
- **TMON/RTCS enhancement**
  - Upload time of burn
  - Upload burn duration
- **TMON will wait to run until uplinked start time, then starts Master RTCS**
- **Still need to generate ephem, get it screened and evaluate results**
- **Timeframe improved**
  - ATC need by 1500-1900z day before
  - TMON patched by 4 hours prior to burn



TMON →
MASTER RTCS →

RTCS/TMON	GMT Time	To be Executed Via TMON Process on 2016 / 105	Rel CMD Timing
TMON 55	13:15:38	*TMON 55 Activation*	(DV - 1:00:01)
RTCS 30	13:15:39	*DMU Master RTCS 30 Activated*	(DV - 1:00:00)
RTCS 180	13:15:39	FS1_DISABLE_NTCH_FLT	(DV - 1:00:00)
	13:15:41	FS1_DISABLE_WSPD_CTL	0:00:02
	13:16:09	GNC_SET_IRUA_HIRATE	0:00:28
	13:16:10	GNC_SET_IRUB_HIRATE	0:00:01
	13:16:11	GNC_SET_IRUC_HIRATE	0:00:01
	13:16:29	FS1_RESET_UPD_FILT	0:00:18
RTCS 181	13:30:39	FS1_RESET_THR_PW_SUM	(DV - 0:45:00)
	13:30:40	TCS_DISABLE_TANK_H1A	0:00:01
	13:30:42	TCS_DISABLE_TANK_H2A	0:00:02
	13:30:44	FS1_DISABLE_TMONGP=17	0:00:02
	13:30:46	TCS_DISABLE_PEPC1HA	0:00:02
	13:30:48	TCS_DISABLE_PEPC3HA	0:00:02
	13:30:50	TCS_DISABLE_PMEA1_HA	0:00:02
	13:30:52	TCS_DISABLE_PMEA2_HA	0:00:02
	13:30:54	TCS_DISABLE_PRPBDUHA	0:00:02
	13:30:56	FS1_ACTIVATE_RTCS=175	0:00:02
	13:31:04	PMS_ENABLE_CAT1LBOD	0:00:08
RTCS 33	13:55:39	CEA_SET_IC_ISEQHOLD	(DV - 0:20:00)
	13:55:40	CEF_SET_IC_ISEQHOLD	0:00:01
	13:56:10	CEA_SET_IC_AZPOS_SP2	0:00:30
	13:56:11	CEF_SET_IC_AZPOS_SP2	0:00:01
	13:56:40	CEA_SET_IC_ISEQCTAM	0:00:29
	13:57:10	CEF_SET_IC_ISEQCTAM	0:00:30
	13:57:20	FS1_SET_INHIBID(18)	0:00:10
	13:57:21	FS1_SET_INHIBID(19)	0:00:01
RTCS 183	14:00:39	FS1_DISABLE_SSST1_UD	(DV - 0:15:00)
	14:00:40	FS1_DISABLE_SSST2_UD	0:00:01
	14:00:41	FS1_DISABLE_FSS_UD	0:00:01
	14:00:49	FS1_DISABLE_NTCH_FLT	0:00:08
	14:00:50	FS1_USE_NOM_ORB_RATE	0:00:01
	14:00:51	FS1_DISABLE_RWA_FF	0:00:01
	14:00:52	FS1_DISABLE_SC_FF	0:00:01
	14:00:53	FS1_DISABLE_MAGUL_FF	0:00:01
	14:00:54	FS1_DISABLE_HGA_FF	0:00:01
	14:00:55	FS1_DISABLE_WSPD_CTL	0:00:01
	14:01:09	FS1_SELECT_HGA_EPA	0:00:14
	14:01:10	FS1_ACTIVATE_RTCS=255	0:00:01
RTCS 34	14:06:39	FS1_DISABLE_DV_BIAS	(DV - 0:09:00)
	14:06:41	PMS_ENABLE_REA1LBOD	0:00:02
	14:06:43	PMS_ARM_REA1LBOD	0:00:02
	14:06:45	PMS_ARM_REA5LBOD	0:00:02
	14:08:39	FS1_SELECT_OA_MODE	0:01:54
	14:10:39	TCS_DISABLE_HCEAGROS	0:02:00
	14:10:41	TCS_DISABLE_CKTAHTA	0:00:02
	14:10:43	TCS_DISABLE_CKTBHTA	0:00:02
	14:10:45	TCS_DISABLE_CKTCHTA	0:00:02
	14:10:47	TCS_DISABLE_CKTDHTA	0:00:02
	14:10:49	TCS_DISABLE_CKTEHTA	0:00:02
RTCS 35	14:15:39	FS1_ENABLE_DV_MNVR	INPUT
	14:16:34	PMS_DISARM_REA5LBOD	0:00:55
	14:16:36	TCS_ENABLE_HCEAGROS	0:00:02
	14:16:38	TCS_ENABLE_CKTABCHTA	0:00:02
	14:16:40	TCS_ENABLE_CKTDEHTA	0:00:02
	14:16:41	FS1_ACTIVATE_RTCS=256	0:00:01
RTCS 184	15:55:39	CEF_SET_IC_ISEQCTRK	1:38:58
RTCS 185	15:55:39	CEA_SET_IC_ISEQCTRK	1:38:58

Process Improvement: Added CRMS [1 of 2]

- **Collision Risk Management System (CRMS) developed by SpaceNav**
- **JSpOC conjunction data retrieved directly from SpaceTrack; optimal burn solutions generated to mitigate any/all HIEs in safety volume**
  - High Interest Event (HIE) threshold is configurable by mission
  - More detailed report generated for HIE and automatically emailed to mission distribution list
- **CRMS outputs multiple burn solutions to our Flight Dynamics team based on configurable constraints (each time new data is received)**
  - EOS uses eight(8) cases: One(1) unconstrained and three(3) constrained over two distinct time periods
    - **Unconstrained** = Optimal; **Constrained Cases** = Burns not to exceed 0, 10 & 20 km WRS control box
    - **Time periods**: TCA – 24 hours and TCA - 3 hours
- **Flight Dynamics automatically builds ephems corresponding to each burn solution**
- **Maneuver ephems get manually/automatically delivered to CARA/JSpOC for screening**
  - "Best" five(5) ephems are sent for screening (manual determination now; soon will be logic based)
- **Screening results are posted to SpaceTrack; CRMS automatically ingests them and emails out the results**

Process Improvement: Added CRMS [2 of 2]

- **The CRMS software has numerous (database configurable) fields and settings that enable mission-specific operations concept (Ops Con)**
- **The settings allow control in the following categories**
  - Pc thresholds for maneuver planning trigger & mitigation target
  - Flags and thresholds to exclude events with stale data or poor OD quality (secondary object)
  - Flags and thresholds for excluding events that are many days in the future
  - Default settings for maneuver trade space & optimal maneuver planning analysis

- **All pertinent conjunction data received in expedited manner**
- **Mitigation solutions identified within minutes of receiving updated data**
- **Ephems are autonomously built (and delivered) for all mitigation solutions**
- **Highly customizable for unique mission constraints**

Future Enhancements/Challenges

- **Enhancements**
  - Streamline data flow to greatest extent possible
    - Preserve Ephem name throughout process
    - Minimize data flow hops and turnaround time
  - Tweak new automation as we gain experience with using it for future DAMs
  - Compute and use maneuver covariance (O/O ephem)

- **Challenges**
  - **Space Fence**
    - What will order of magnitude increase looks like in terms of workload?
    - How many objects that are single station tracked?
    - Will we be able to believe data enough to make maneuver decisions on?
    - What will evaluation/decision workload look like in that environment?
  - **More collisions/debris**
  - **Post maneuver concerns shortly after maneuver (completed or planned)**
    - Nominal Orbital Maintenance Maneuver (DMU or IAM)
    - Debris Avoidance Maneuver

Conclusions/Lessons Learned

- **Fully understand mission capabilities, orbit requirements & constraints**
- **Understand planning, execution & support group timelines and condense them as much as possible**
  - Reduces workload on teams
  - Allows for maximum data about the conjunction(s)
  - Can react to short notice events
- **Determine the decision data needed and mission risk posture**
- **Document and Evolve process**
  - Push toward automated solutions as much as possible

Executive Summary

- **Debris Avoidance Maneuver (DAM) decisions are complex with lots at stake**
- **A Mission Director (MD) must consider all factors involved, to make the best decision**
  - High Level factors include the science objectives of the platform, orbit maintenance requirements & mission constraints
  - For EOS missions, information and products are received from the Flight Team, Flight Dynamics, Conjunction Analysts (CARA/JSpOC) & Instrument teams, so a MD must be familiar with the timelines for each group to support a DAM
  - Ensuring that all data needed to make a decision is gathered and having predefined risk thresholds is also key
- **Finally, an MD must be able to synthesize and comprehend all the inputs & conjunction details to make the final decision**
- **Due to these complexities, it is important to have a documented process and follow it consistently**
- **As the debris environment, sensor capabilities and analytics evolve, it is important to evolve the decision process and tools as well**
  - ESMO has worked hard to minimize turnaround time & workload
  - Moving towards automated maneuver solutions for each High Interest Event (HIE) with ramp up and decision point within 24 hours of TCA

Acronym List

- **ATC** – Absolute Time Commands
- **CA** – Collision Avoidance
- **CARA** – Conjunction Analysis Risk Assessment
- **CRMS** – Collision Risk Management System
- **DAM** – Debris Avoidance Maneuver
- **DMUM** – Drag Make-Up Maneuver
- **EOS** – Earth Observing System
- **ESMO** – Earth Science Mission Operations
- **IAM** – Inclination Adjust Maneuver
- **JSpOC** – Joint Space Operations Center
- **MOWG** – Mission Operations Working Group
- **OD** – Orbit Determination
- **O/O –** Owner/Operator
- **Pc** – Probability of Collision
- **RTCS** – Relative Time Command Sequence
- **SMA** – Semi Major Axis
- **TCA** – Time of Closest Approach
- **TMON** – Telemetry Monitor
- **WRS** – World Reference System

Questions

Process Flow Description

- **CARA reviews and updates tasking for all objects in the volume throughout entire 7 day span**
- FDS provides Delta-V Budgets and required products daily to CRMS autonomously
- CRMS downloads SpaceWeather related items autonomously
- OSAs posts CDM/VCM to SpaceTrack
- CRMS downloads CDM/VCM from SpaceTrack autonomously

If Conjunction exceeds mission defined threshold, CRMS identifies maneuver options based on maneuver constraints.
Once per day between 24 hours and 72 hours:

- FDS **auto** generates maneuver ephems based on CRMS maneuver options
  - Options will be (8 Total):
    - 24 hours prior → Optimized solution, 0km, 10km & 20km
    - Orbit before TCA → Optimized solution, 0km, 10km & 20km
- FDS personnel makes manual determination of which to send to CARA (Phase 1) ---> Phase 2 delivery will be automatic
- **CARA sends to JSpOC for screening**
- OSAs posts screening results on SpaceTrack & send to CARA (**CARA review of screening results only by request**)
  - Special Case: If conjunction is complex, CARA will be notified for additional assistance
- CRMS will ingest screening results and generate report
- ESMO reviews report and determines if any other options/solutions are warranted (kick off manual process)
  - Special Case: If DAM screening reveals new post maneuver conjunction, then tasking eval may be needed by CARA

If less than 24 hours:

- FDS generates maneuver ephems
- OSA screens, posts results on SpaceTrack
- **CARA reviews screening results**
  - Determine if mitigation options are acceptable
  - Identify alternate option if current mitigation options are insufficient
  - Support CAM

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High Level Roles and Responsibilities

CARA Orbital Safety Analyst (OSA) @ JSpOC Responsibilities:

- Post CDM/VCMs to SpaceTrack (reg update, 1v1s or screening results)
- Perform screenings
- Perform manual OD adjustments as required
- Adjudicate tasking levels for catalog objects

NASA CARA Analyst Responsibilities:

- Investigate Conjunctions that are high risk or have space weather concerns
  - Request elevated tasking or 1v1s as appropriate
- Communicate risk to mission management
- Analyze High Risk Conjunctions & associated maneuver options (as requested)
- Develop High Interest Event (HIE) Briefings
- Support Maneuver Command Authorization Meetings (CAMs)

Space Track (Air Force managed):

- Interface to Data (requires login)

ESMO Flight Dynamics Responsibilities:

- Provides delta-v buffers
- Maneuver Planning (Generate & Deliver Ephemerides)

ESMO Collision Risk Management System (CRMS) **responsibilities** (developed by SpaceNav):

- Automated conjunction risk reduction balancing Collision Risk and Mission Requirements
  - Generate maneuver options & associated reports