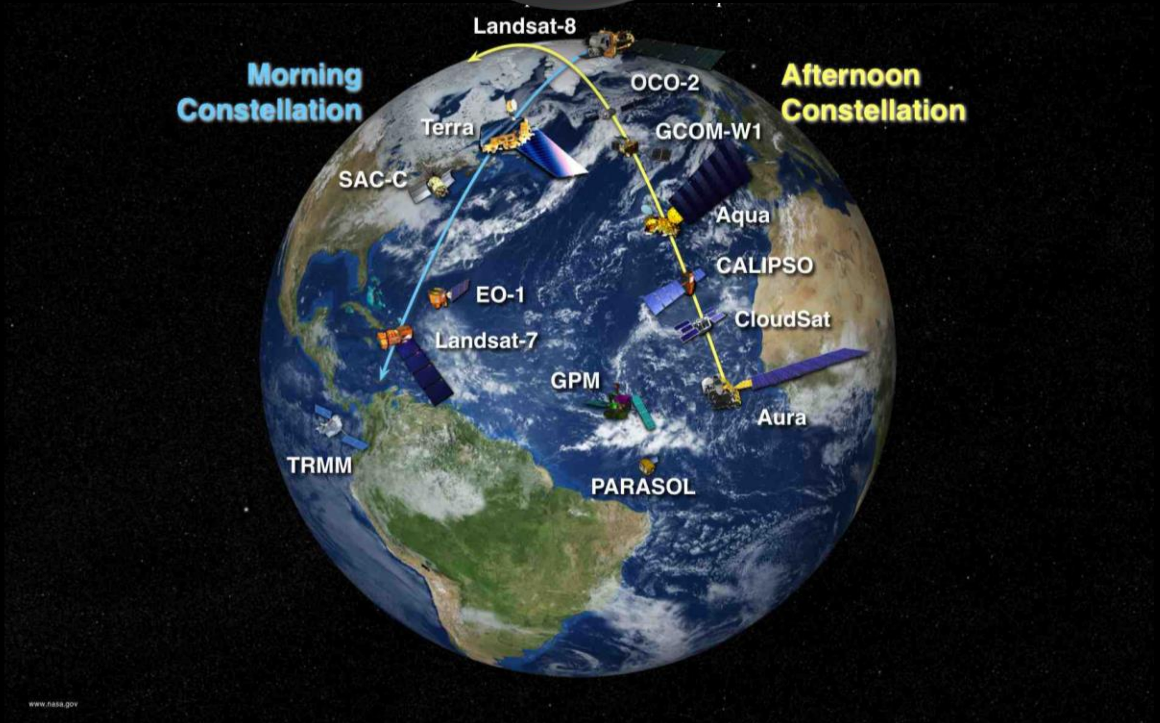

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Aqua/Aura Updated Inclination Adjust Maneuver Performance Prediction Model

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Agenda

- Introduction
- Motivation for New Prediction Model
  - Aqua Performance History
  - Aura Performance History
- Previous Trending Models
- New Model
- Results
- Implementation
- Conclusion

Introduction

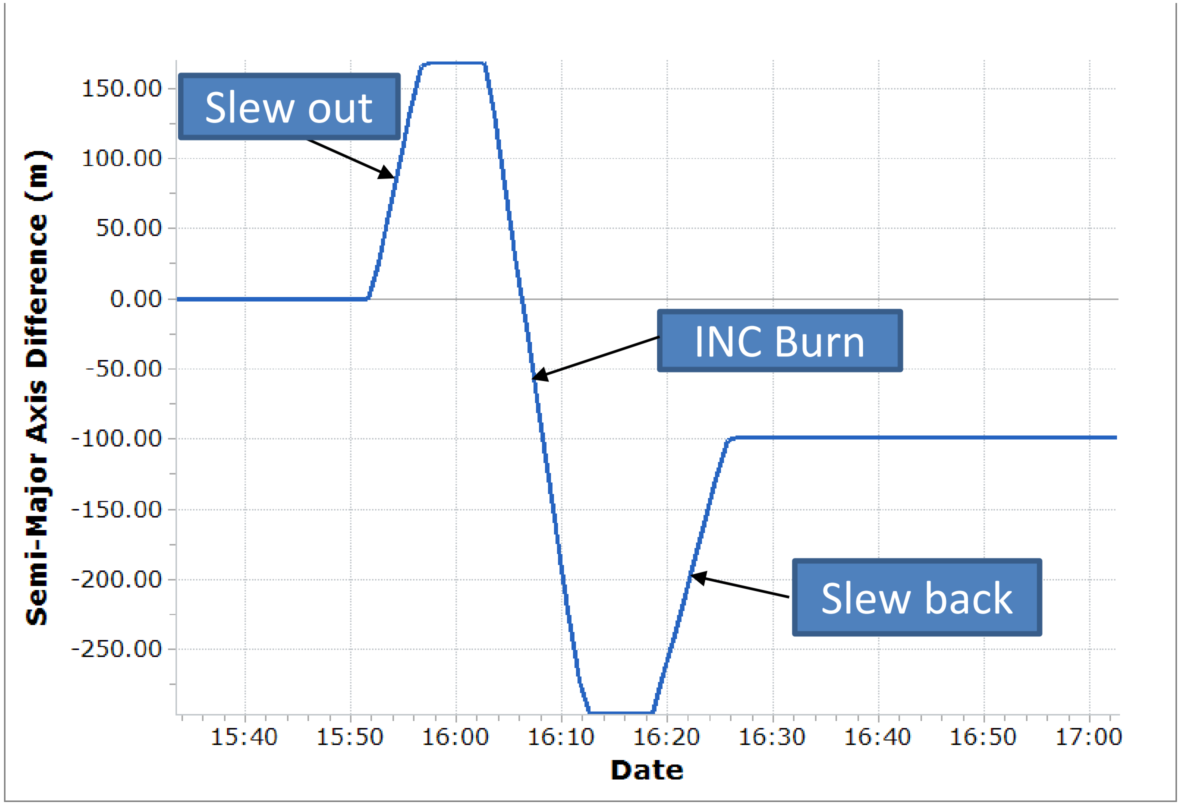
- For the previous two Inclination Adjust Maneuver (IAM) series, ΔSemi Major Axis (ΔSMA) and ΔInclination (ΔI) predictions were less accurate than desired for both Aqua and Aura.
  - **24.0 meter** average error in ΔSMA predictions and **0.95%** average error in ΔI predictions for Aqua.
  - **11.8 meter** average error in ΔSMA predictions and **1.79%** average error in ΔI predictions for Aura.

Introduction

- In addition, Aqua had performed six large slew angle IAMs; these needed to be incorporated into the maneuver performance prediction model, or separated into a different prediction method.
- Aura's last five IAMs consistently performed 2-2.5% cold.
  - As a result, in order to maintain phasing with Aqua, Aura was required to perform all its routine drag make-up (DMU) maneuvers in 2017 at the descending node.
- The performance prediction models were not always accurately predicting maneuver performance.
- An analysis was performed in which a new prediction model with improved results was developed.

Background

- Aqua and Aura use thruster-based slews to perform IAMs.
- As a result, the slew segments of the maneuver contribute to the total ΔSMA performance, as shown in the figure below, which increases the difficulty in accurately predicting the achieved ΔSMA.



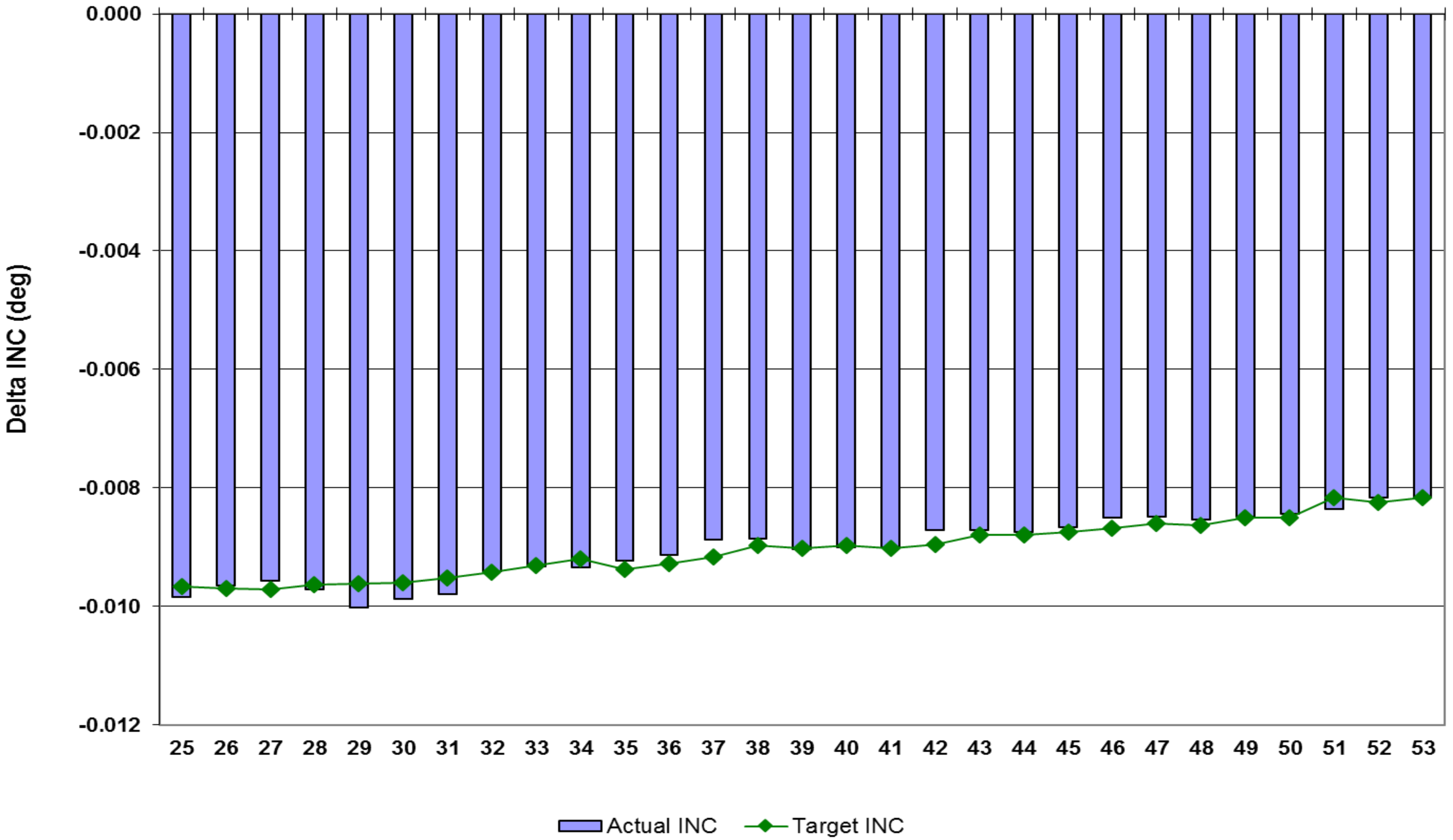
Aqua Performance History

	Planned ΔSMA	Achieved ΔSMA	ΔSMA Error	Planned ΔI	Achieved ΔI	Percent Error*
	m	m	m	deg	deg	%
INC#48	41.3	38.8	-2.5	-0.00863	-0.008538	0.91% HOT
INC#49	44.5	51.3	6.8	-0.00851	-0.008483	0.13% HOT
INC#50	-55.4	-9.4	46.0	-0.00851	-0.008357	2.41% COLD
INC#51	-64.3	-66.5	-2.2	-0.00816	-0.008326	2.20% HOT
INC#52	13.7	18.1	4.4	-0.00825	-0.008222	0.44% COLD
INC#53	11.1	51.9	40.8	-0.00817	-0.008177	0.12% HOT
INC#54	-105.0	-24.2	80.8	-0.00840	-0.008241	2.55% COLD
INC#55	-99.1	-107.9	-8.8	-0.00810	-0.008090	0.21% COLD

Average |ΔSMA Error|: 1-σ Error Bound:	**24.0 m ± 36.1 m**	**Average |ΔI % Error|: 1-σ Error Bound:**	**0.95% ± 1.22%**

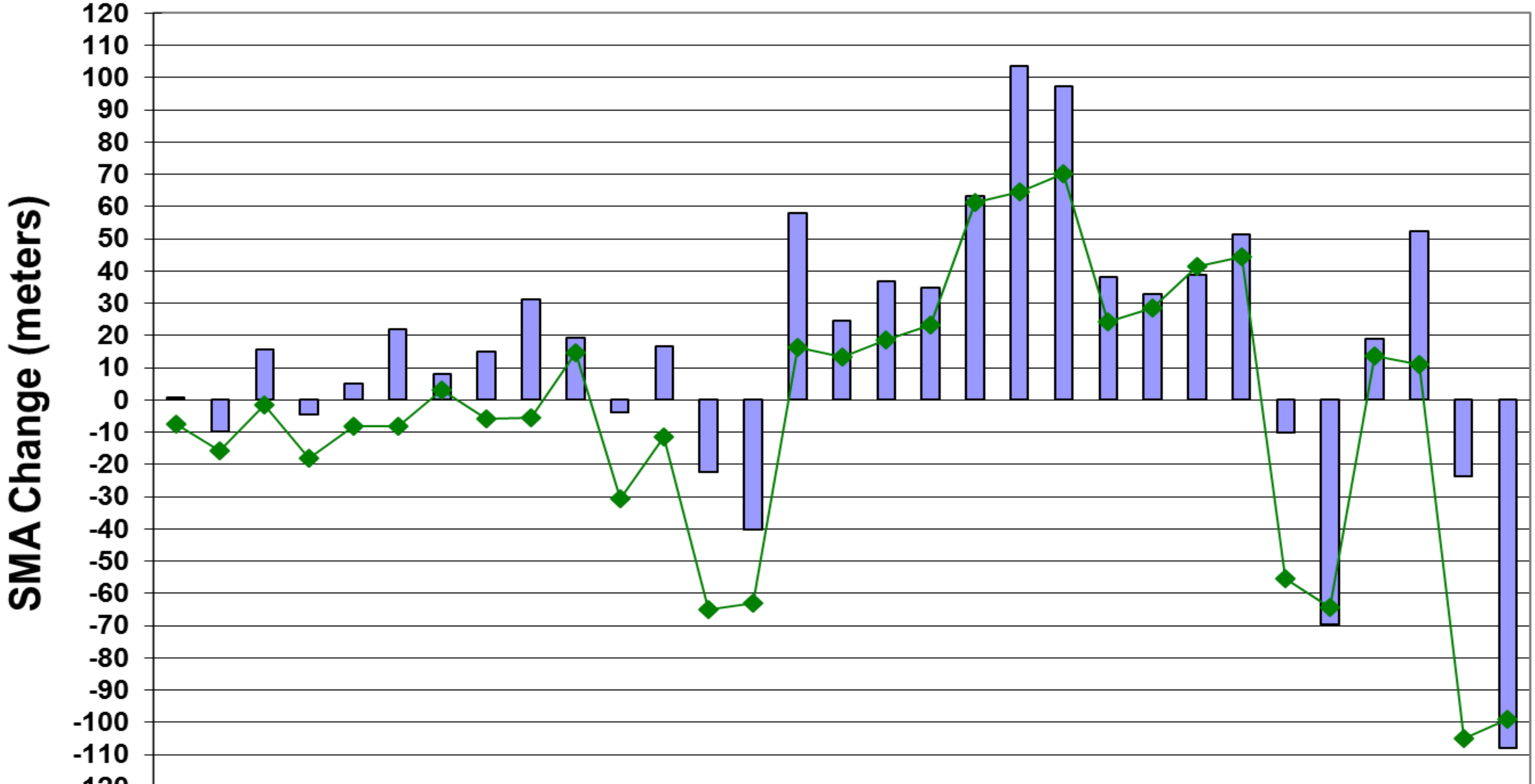
*Hot/cold performance characterization refers to more/less achieved negative ΔI than planned for.

Aqua IAM Performance: Delta-Inclination



Aqua Performance History

Aqua IAM Performance: Delta-SMA



	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Actual SMA	0.750	-9.90	15.75	-4.51	4.890	21.75	8.082	14.97	31.10	19.21	-3.80	16.65	-22.5	-40.2	58.00	24.70
Target SMA	-7.57	-15.7	-1.60	-18.0	-8.28	-8.04	3.114	-5.96	-5.52	14.76	-30.6	-11.4	-65.0	-62.9	16.30	13.30
Com. Yaw	-83.4	-83.6	-83.3	-83.7	-83.5	-83.5	-83.3	-83.5	-83.6	-83.2	-84.2	-83.8	-85.0	-85.0	-83.3	-84.2

	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
Actual SMA	36.70	34.80	63.25	103.5	97.35	38.12	32.75	38.80	51.30	-10.2	-69.5	18.85	52.30	-23.7	-107.
Target SMA	18.60	23.29	61.30	64.50	70.25	24.23	28.58	41.25	44.50	-55.4	-64.2	13.65	11.12	-105.	-99.1
Com. Yaw	-84.2	-84.2	-83.4	-83.4	-83.4	-84.8	-84.8	-85.0	-85.0	-88.0	-89.5	-87.3	-87.3	-90.3	-92.5

Aura Performance History

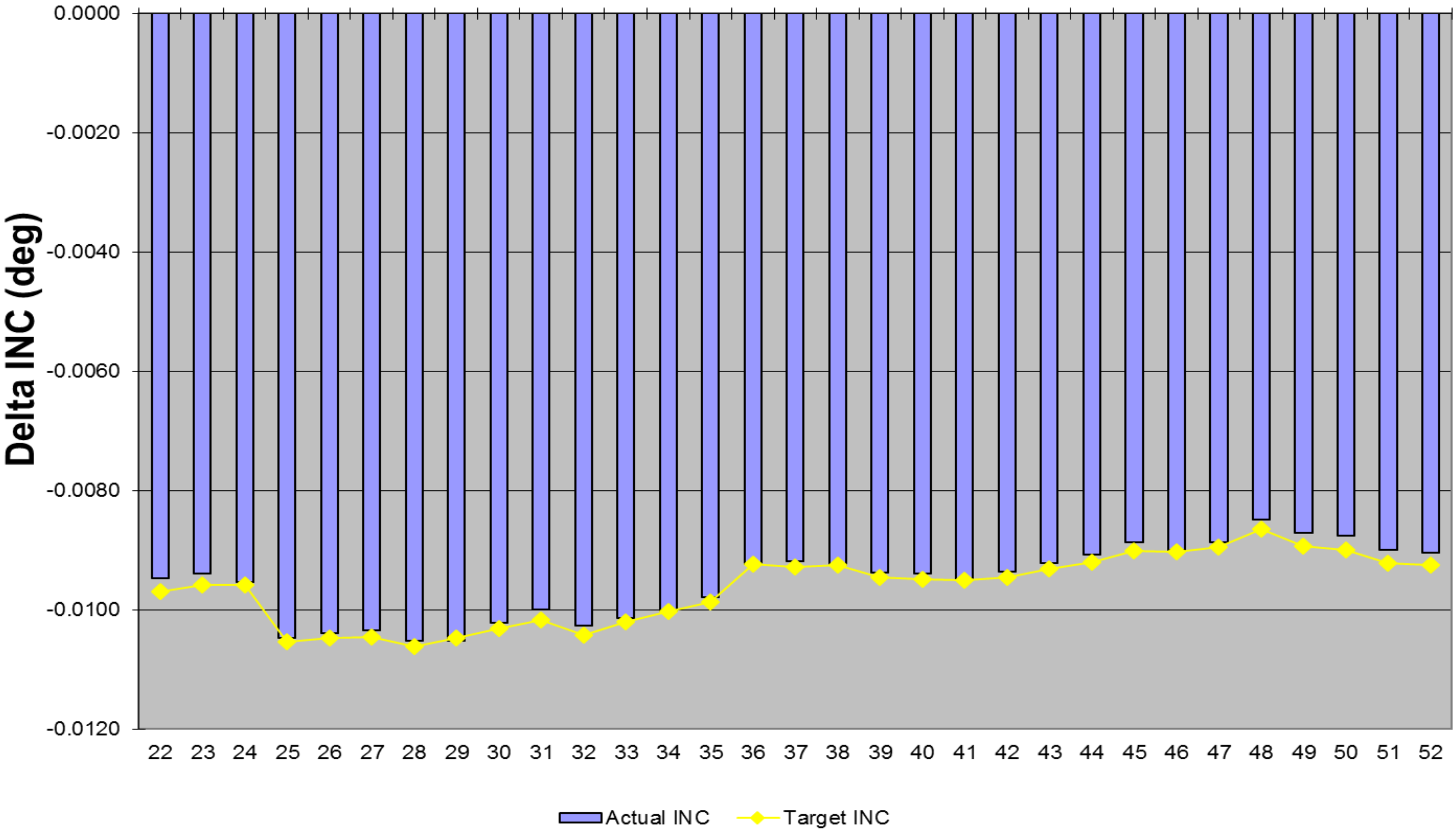
	Planned ΔSMA	Achieved ΔSMA	ΔSMA Error	Planned ΔI	Achieved ΔI	Percent Error*
	m	m	m	deg	deg	%
INC#48	45.0	41.8	3.2	-0.009007	-0.008870	1.52% COLD
INC#49	21.3	13.6	7.7	-0.009030	-0.008990	0.44% COLD
INC#50	1.3	-23.5	24.8	-0.008948	-0.008875	0.82% COLD
INC#51	27.2	9.9	17.3	-0.008650	-0.008490	1.85% COLD
INC#52	13.1	14.1	1.0	-0.008928	-0.008715	2.39% COLD
INC#53	20.1	8.6	11.5	-0.009000	-0.008750	2.78% COLD
INC#54	15.8	1.0	14.8	-0.009210	-0.008990	2.39% COLD
INC#55	-9.1	-23.5	14.4	-0.009245	-0.009050	2.11% COLD

Average |ΔSMA Error|:	**11.8 m**	**Average |ΔI % Error|:**	**1.79%**
1-σ Error Bound:	**± 13.9 m**	**1-σ Error Bound:**	**± 1.94%**

*Hot/cold performance characterization refers to more/less achieved negative ΔI than planned for.

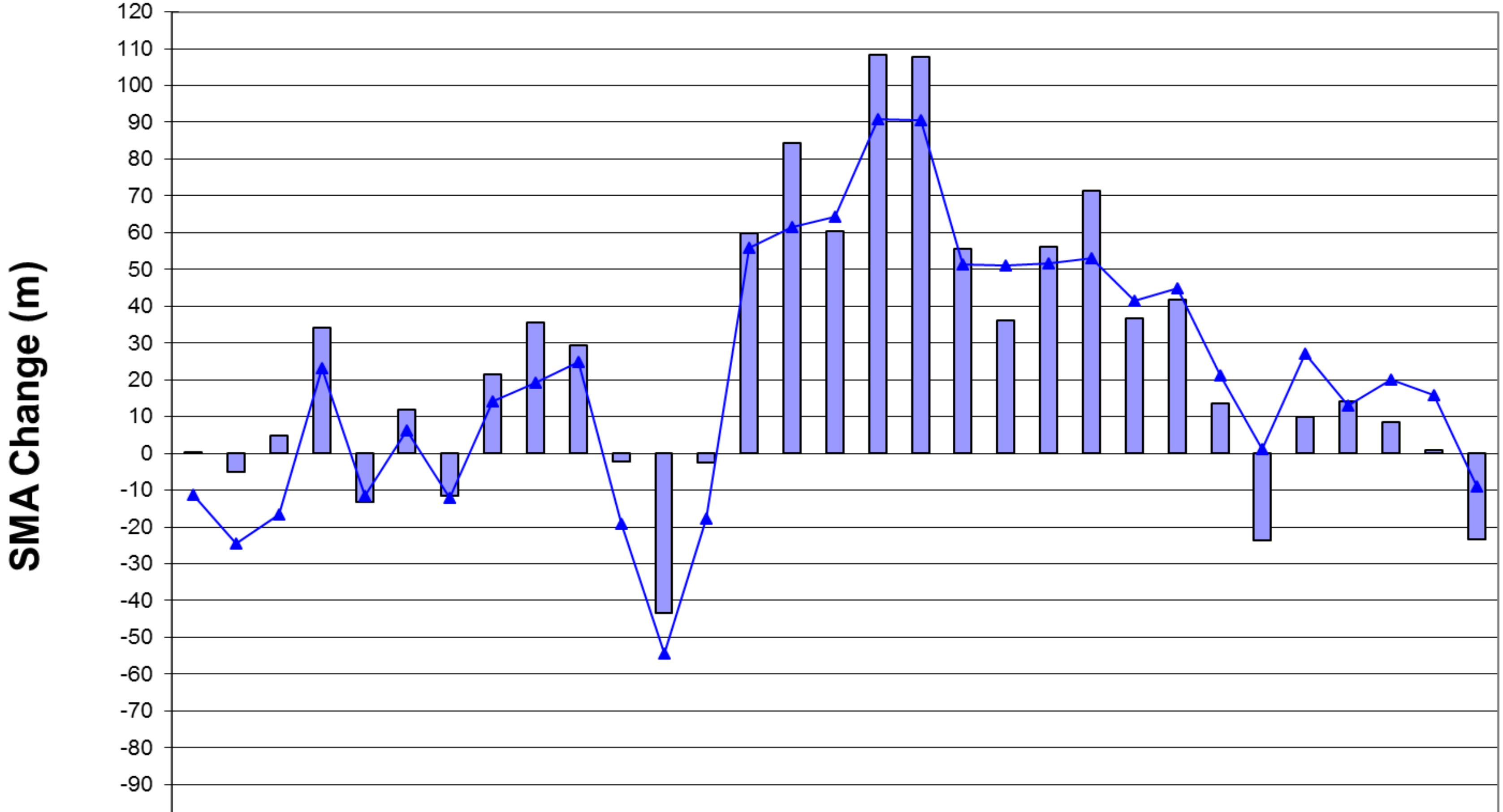
Aura Performance History

Aura IAM Performance: Delta-Inclination



Aura Performance History

Aura IAM Performance: Delta-SMA



	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Actual SMA	0.017	-4.94	4.935	34.03	-13.3	11.87	-11.5	21.41	35.61	29.35	-2.26	-43.3	-2.55	59.75	84.23
Target SMA	-11.3	-24.6	-16.5	23.12	-11.6	6.228	-12.1	14.18	19.23	24.97	-19.2	-54.2	-17.7	55.99	61.63
Com. Yaw	-84.3	-84.7	-84.6	-83.2	-84.0	-83.6	-83.8	-83.2	-83.1	-83.0	-84.0	-84.8	-84.0	-82.4	-82.6

	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
Actual SMA	60.50	108.3	107.7	55.50	36.25	56.10	71.50	36.75	41.75	13.57	-23.5	9.905	14.10	8.600	1.000	-23.5
Target SMA	64.29	90.90	90.50	51.50	51.10	51.63	52.95	41.63	44.98	21.30	1.284	27.20	13.10	20.10	15.80	-9.10
Com. Yaw	-82.7	-81.5	-81.5	-82.9	-83.0	-82.7	-82.7	-83.2	-83.2	-84.0	-85.0	-84.2	-83.8	-83.8	-83.8	-84.5

IAM Performance Prediction Model

- The purpose of the maneuver performance prediction model is to accurately predict:
  - Duty cycles (DCs) for each thruster for the slew-out, inclination burn, and slew-back segments of maneuver
    - DCs represent the proportion of time that the thruster is firing for a given maneuver segment.
  - Thrust scale factors (TSFs) for the slew-out and inclination burn (for Aqua and Aura), and slew-back (Aura only) segments
    - TSFs are intended to correct our model to match the observed performance, and capture degradation of performance over time.
    - For Aqua, we use the slew-out TSF prediction for both the slew-out and slew-back segments.
  - The average pitch, roll, and yaw errors for the inclination burn segment
  - The slew-back and slew-out segment durations

Previous Prediction Models

- The previous prediction model for Aqua was developed in 2014. In this model, duty cycles and TSFs were estimated using polynomial relationships with parameters such as maneuver number (proxy for tank mass), targeted yaw angle, and the slew-out and slew-back segment durations.
- These relationships were found by manually testing various polynomial combinations of these parameters. The combinations yielding the best results when re-planning past IAMs were selected for the prediction equations.
- The previous prediction model for Aura involved taking long-term averages for each variable.
  - Until recently, Aura's maneuvers had not experienced the thruster degradation seen on Aqua's maneuvers.

Review of Previous Trending Models

- The Aqua trending model developed in 2014 yielded improved maneuver performance at the time.
- This method was not used to predict the performance of the large slew angle maneuvers in the 2016 and 2017 IAM series, since it did not take into account the longer commanded slew out and slew back durations.
- The main issues with the previous prediction models were:
  - The Aqua ΔSMA predictions used for the large slew angle maneuvers were not accurate (24.0 m average error).
  - Aura's trending method yielded consistently cold maneuver performance.
- The models for both Aqua and Aura needed to be adjusted in order to reduce overall error, and to better predict future large slew angle maneuver performance.

Improving the Model

- In developing the new prediction model, there were several factors we looked to improve on.
  - Most importantly, we looked to improve our IAM performance predictions.
  - We wanted to move away from using non-physical trending parameters in our model, such as maneuver number (proxy for tank mass) and targeted yaw angle.
  - The 2014 methodology for developing and updating a new prediction model did not adapt well to new factors being considered in maneuver planning (e.g., large slew angle maneuvers and increased burn durations for Aqua in 2018). A more adaptive method would reduce the time required for future trending update efforts.

Improving the Model

- A first attempt at developing a new trending model was done for both Aqua and Aura using a method similar to the one used to develop Aqua's previous trending equations.
- However, there was difficulty in finding relationships with satisfactory improvements for both spacecraft, particularly in predicting the performance of the large slew angle maneuvers for Aqua.

Improving the Model

- Parameters that were not being considered in the model could be contributing to Aqua's IAM performance:
  - In-plane and out-of-plane components of the thrust vector
  - Inclination burn node offset
- Using the prior methodology to develop performance prediction equations, it was time-consuming to search for and identify a best-fit predictive relationship for each variable. This was especially true when considering a larger number of parameters – and polynomial combinations of these parameters – at different orders.

Regression Methods

- In order to more quickly and efficiently identify best-fit trends, we investigated using various statistical regression methods:
  - Polynomial regression
  - Multivariate linear regression
  - Stepwise regression
- Stepwise regression was found to be the most suitable tool.
- Stepwise regression is a method of fitting regression models in which the choice of predictive parameters is carried out by an automatic procedure.

Stepwise Regression

- In a stepwise regression scheme, the trending “model” starts with no parameters.
- The addition of each parameter and parameter combination is tested; the parameter that gives the most statistically significant improvement (smallest probability value) of the fit is included in the model. The process is repeated until no parameter addition would improve the model to a statistically significant extent.
- Essentially, all possible relationships are tested, and only the best-fit relationships are selected to be included in the trending equations.

Parameters to Consider

- The requirement for considering a parameter in the model is that it can be predicted prior to the maneuver.
- The total number of parameters is 10 for Aura and 9 for Aqua:
  - Pre-maneuver total satellite mass
  - Fuel mass consumed to date
  - Commanded yaw angle
  - Commanded slew-out and slew-back segment durations
  - Inclination burn segment duration (Aura only, may be added for Aqua after 2018 series)
  - Commanded thrust direction (commanded yaw angle + thruster offset)
  - Sine and cosine of commanded thrust direction, representing the out-of-plane and in-plane components of the inclination burn, respectively
  - Inclination burn node offset

Advantages of Stepwise Regression

- The stepwise regression method allows for relationships for all combinations of parameters to be rapidly and efficiently tested. This allows us to identify best-fit relationships that would be difficult to find intuitively, or tedious to search for manually.
- This new method is far more adaptive: the effort required to update the trending model when new variables are introduced is greatly reduced. It also allows us to use the same model for all maneuvers, including the large slew angle maneuvers.
- However, as with previous methods, the stepwise regression model would not be able to predict the effect of modifying a parameter that has been constant for all previous IAMs, without using fully-calibrated simulations.

Results

- In order to validate the new model, all IAMs from the previous two series (2016 and 2017 series) were recreated with the new duty cycle and TSF estimates.
- In developing the final trending equations for Aqua and Aura, all data starting from the 2013 IAM series was used.
- For both Aqua and Aura, the new model yields an improved prediction of maneuver performance.

Results Summary

- A comparison of the new and old performance prediction results for the past two IAM series can be found in the table below:

		Average ΔSMA Error	1-σ ΔSMA Error Bound	Average ΔI % Error	1-σ ΔI Error Bound
		m	m	%	%
AQUA	Planned results using old model	24.0	± 36.1	0.95 %	± 1.22 %
AQUA	Results using new model	8.4	± 10.7	0.79 %	± 0.99 %
AURA	Planned results using old model	11.8	± 13.9	1.79 %	± 1.94 %
AURA	Results using new model	4.6	± 5.5	0.72 %	± 0.78 %

Implementation

- The new models were straightforward to implement operationally and in our lifetime analysis scripts.
- These models were used to generate the updated lifetime predictions for Aqua and Aura.
- The process for implementing new equations and/or best-fit coefficients in operational and lifetime scripts is now streamlined.
  - The equations and best-fit coefficients are contained in separate input files, which can easily be modified or replaced.

Conclusions

- A new IAM performance prediction model was developed using stepwise regression to search for and identify the best maneuver performance trends.
- This yields large improvements in inclination maneuver performance predictions.
  – Aqua: From **24.0 m** error in SMA predictions and **0.95%** error in delta-INC prediction, to **8.4 m** and **0.79%** error.
  – Aura: From **11.8 m** error in SMA predictions and **1.79%** error in delta-INC predictions, to **4.6 m** and **0.72%** error.

Conclusions

- The new method could also be used to verify observed trends (or identify new ones) in DMU maneuver planning.
- The new model is far more adaptive than previous models; as a result, the effort required to update the prediction model when new variables are introduced is greatly reduced.

BACKUP

Stepwise Regression - Variables and Parameters

- Variables to estimate in stepwise regression model:
  - Slew out, inclination burn TSFs (Aqua and Aura)
  - Slew back TSF (Aura only)
  - Slew out, inclination burn, and slew back duty cycles for thrusters 1-4
  - Slew out and slew back durations.
  - Average roll and pitch errors for inclination segment.
  - Average yaw offset from commanded yaw angle for inclination segment

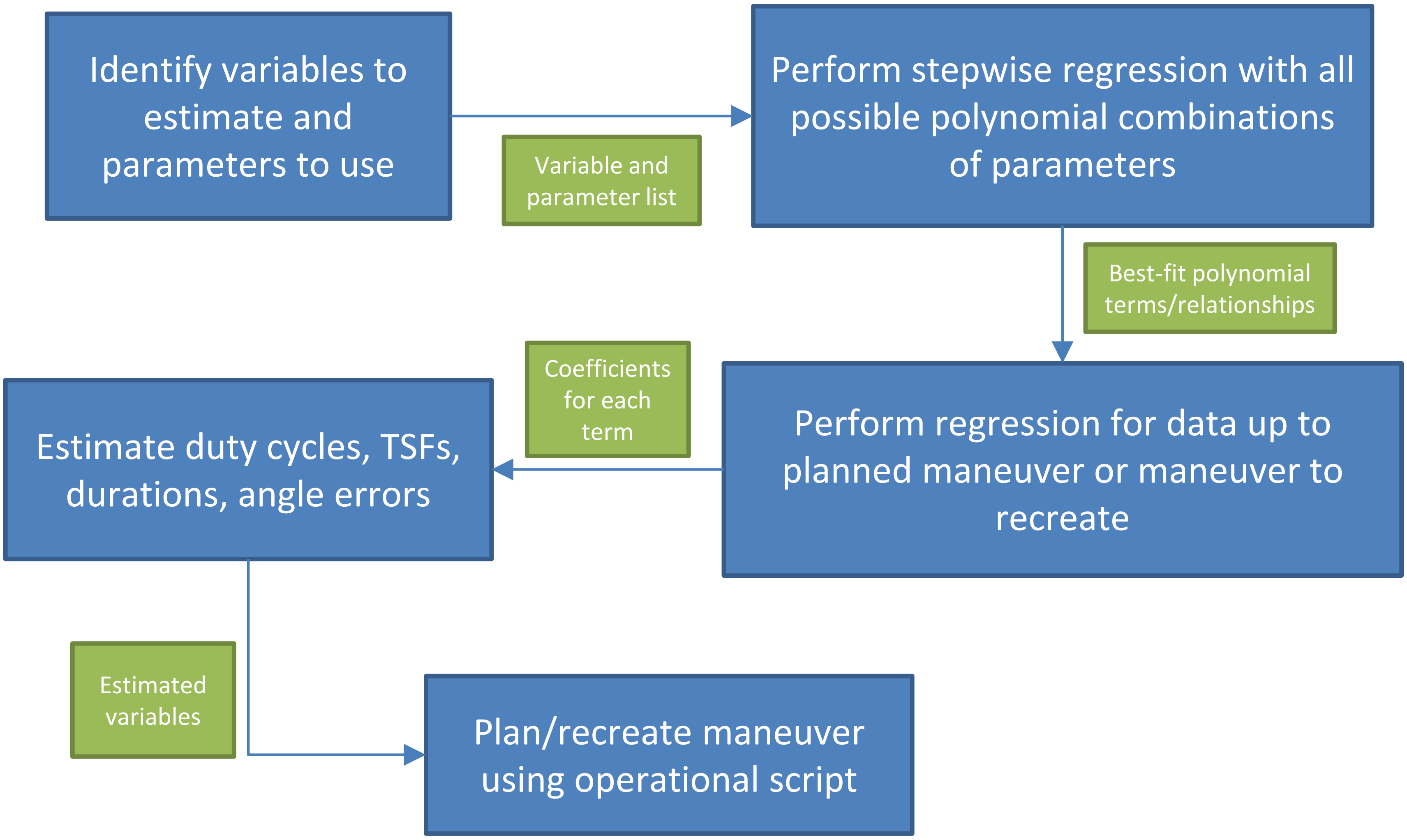
Stepwise Regression - Variables and Parameters

- Parameters to consider in stepwise regression model:
  - Total satellite mass
  - Fuel consumed to date
  - Commanded yaw angle
  - Commanded slew out and slew back durations
  - Inclination burn duration (Aura only, may be added for Aqua after 2018 series)
  - Commanded thrust direction (commanded yaw angle + thruster offset)
  - Sine and cosine of commanded thrust direction, representing the out-of-plane and in-plane components of the inclination burn segment, respectively
  - Inclination burn node offset

Stepwise Regression - Variables and Parameters

- The average pitch, roll and yaw angle errors for the inclination burn segment are a result of the relationship between the various thruster duty cycles for each segment.
- In the stepwise regression model, these duty cycles are added as additional parameters in developing the equations to estimate the angle errors. This helps give a more accurate estimate of the angle errors.
- For the re-planned or predicted maneuver, once the duty cycle estimations are calculated they are subsequently included as parameters in estimating the angles.

Stepwise Regression – Logic Flow



Results – Aqua

- The table below shows the resulting errors in recreating the past two IAM series (2016 and 2017 series), when developing trending equations using all data starting from the series in the left column.
- The row in red shows the span used to develop the final model. This was chosen as a compromise of the best ΔSMA and ΔI performance.

New trending using IAMS starting from:	Average ΔSMA Error	1-σ ΔSMA Error Bound	Average ΔI % Error	1-σ ΔI Error Bound
	m	m	%	%
INC#25 (2010)	11.6	± 12.9	0.70 %	± 0.81 %
INC#31 (2012)	11.1	± 12.5	0.73 %	± 0.85 %
INC#35 (2013)	**8.4**	**± 10.7**	**0.79 %**	**± 1.00 %**
INC#39 (2014)	12.2	± 13.7	0.76 %	± 0.88 %

Planned results using old trending	**24.0**	**± 36.1**	**1.12 %**	**± 1.51 %**

Aqua – Allowed Parameters Chart

Variable/Parameter		Pre-maneuver Fuel Used	Pre-maneuver Total Mass	Commanded Yaw	Commanded Slew Out Dur.	Commanded Slew Back Dur.	Commanded Yaw Thrust Dir.	sin(Commanded Yaw thrust Dir.)	cos(Commanded Yaw Thrust Dir.)	Node Offset
Slew Out	TSF	1	1	1	1	1	1	1	1	1
	DC1	1	1	1	1		1	1	1	1
	DC2	1	1	1	1		1	1	1	1
	DC3	1	1	1	1		1	1	1	1
	DC4	1	1	1	1		1	1	1	1
	Duration	1	1	1	1		1	1	1	1
Inc	TSF	1	1	1	1	1	1	1	1	1
	DC1	1	1	1	1	1	1	1	1	1
	DC2	1	1	1	1	1	1	1	1	1
	DC3	1	1	1	1	1	1	1	1	1
	DC4	1	1	1	1	1	1	1	1	1
Slew Back	DC1	1	1	1		1	1	1	1	1
	DC2	1	1	1		1	1	1	1	1
	DC3	1	1	1		1	1	1	1	1
	DC4	1	1	1		1	1	1	1	1
	Duration	1	1	1		1	1	1	1	1
Inc Angles	Roll	1	1	1	1	1	1	1	1	1
	Pitch	1	1	1	1	1	1	1	1	1
	Yaw offset from commanded	1	1	1	1	1	1	1	1	1

Aqua – Parameters Chart

Variable/Parameter		Pre-maneuver Fuel Used	Pre-maneuver Total Mass	Commanded Yaw	Commanded Slew Out Dur.	Commanded Slew Back Dur.	Commanded Yaw Thrust Dir.	sin(Commanded Yaw thrust Dir.)	cos(Commanded Yaw Thrust Dir.)	Node Offset
Slew Out	TSF	1		1						
	DC1	1		1					1	1
	DC2	1							1	1
	DC3	1		1	1				1	1
	DC4	1							1	1
	Duration								1	1
Inc	TSF	1		1					1	1
	DC1	1		1						
	DC2	1		1			1		1	1
	DC3	1		1	1				1	1
	DC4	1				1				
Slew Back	DC1	1	1							
	DC2	1								1
	DC3	1		1		1				
	DC4	1				1				
	Duration					1	1	1		
Inc Angles	Roll	1								
	Pitch		1							1
	Yaw offset from commanded	1								

Aqua – Parameters Chart

Variable/ Parameter	Slew Out				Inc. Burn				Slew Back			
	DC1	DC2	DC3	DC4	DC1	DC2	DC3	DC4	DC1	DC2	DC3	DC4
Roll					1			1		1		
Pitch					1	1	1	1		1		
Yaw offset from commanded					1	1	1	1			1	

Aura – Allowed Parameters Chart

Variable/Parameter		Pre-maneuver Fuel Used	Pre-maneuver Total Mass	Commanded Yaw	Inclination Burn Dur.	Commanded Slew Out Dur.	Commanded Slew Back Dur.	Commanded Yaw Thrust Dir.	sin(Commanded Yaw thrust Dir.)	cos(Commanded Yaw Thrust Dir.)	Node Offset
Slew Out	TSF	1	1	1	1	1		1	1	1	1
	DC1	1	1	1	1	1		1	1	1	1
	DC2	1	1	1	1	1		1	1	1	1
	DC3	1	1	1	1	1		1	1	1	1
	DC4	1	1	1	1	1		1	1	1	1
	Duration	1	1	1	1	1		1	1	1	1
Inc	TSF	1	1	1	1	1	1	1	1	1	1
	DC1	1	1	1	1	1	1	1	1	1	1
	DC2	1	1	1	1	1	1	1	1	1	1
	DC3	1	1	1	1	1	1	1	1	1	1
	DC4	1	1	1	1	1	1	1	1	1	1
Slew Back	TSF	1	1	1	1		1	1	1	1	1
	DC1	1	1	1	1		1	1	1	1	1
	DC2	1	1	1	1		1	1	1	1	1
	DC3	1	1	1	1		1	1	1	1	1
	DC4	1	1	1	1		1	1	1	1	1
	Duration	1	1	1	1		1	1	1	1	1
Inc Angles	Roll	1	1	1	1	1	1	1	1	1	1
	Pitch	1	1	1	1	1	1	1	1	1	1
	Yaw offset from commanded	1	1	1	1	1	1	1	1	1	1

Aura – Parameters Chart

Variable/Parameter		Pre-maneuver Fuel Used	Pre-maneuver Total Mass	Commanded Yaw	Inclination Burn Dur.	Commanded Slew Out Dur.	Commanded Slew Back Dur.	Commanded Yaw Thrust Dir.	sin(Commanded Yaw thrust Dir.)	cos(Commanded Yaw Thrust Dir.)	Node Offset
Slew Out	TSF										
	DC1										
	DC2	1								1	
	DC3										
	DC4	1								1	
	Duration	1								1	
Inc	TSF		1				1				
	DC1	1			1						
	DC2		1		1		1		1		
	DC3	1	1		1		1				
	DC4	1		1	1						
Slew Back	TSF		1				1		1		
	DC1						1				
	DC2										
	DC3		1				1				
	DC4		1				1		1		
	Duration		1				1				
Inc Angles	Roll										
	Pitch										
	Yaw offset from commanded	1	1		1		1	1		1	

Aura – Parameters Chart

Variable/ Parameter	Slew Out				Inc. Burn				Slew Back			
	DC1	DC2	DC3	DC4	DC1	DC2	DC3	DC4	DC1	DC2	DC3	DC4
Roll						1	1					1
Pitch				1		1	1				1	1
Yaw offset from commanded	1			1	1							

Trend Statistics and Properties

Variable/ Parameter		Aqua				Aura			
		Max term order	Number of terms considered	Number of terms in equation	R2 value	Max term order	Number of terms considered	Number of terms in equation	R2 value
Slew Out	TSF	3	4950	1	0.74	3	4950	0	0.00
	DC1	3	3408	2	0.92	3	4950	0	0.00
	DC2	3	3408	2	0.90	3	4950	1	0.46
	DC3	3	3408	2	0.89	3	4950	0	0.00
	DC4	3	3408	2	0.71	3	4950	1	0.29
	Duration	3	3408	1	0.32	3	4950	1	0.39
Inc	TSF	3	4950	2	0.90	3	6900	1	0.78
	DC1	3	4950	3	0.91	3	6900	1	0.36
	DC2	3	4950	2	0.59	3	6900	2	0.73
	DC3	3	4950	2	0.57	3	6900	2	0.97
	DC4	3	4950	1	0.60	3	6900	1	0.82
Slew Back	TSF	3	n/a	n/a	n/a	3	4950	1	0.78
	DC1	3	3408	1	0.90	3	4950	1	0.30
	DC2	3	3408	1	0.88	3	4950	0	0.00
	DC3	3	3408	1	0.85	3	4950	1	0.49
	DC4	3	3408	1	0.73	3	4950	1	0.25
	Duration	3	3408	2	0.98	3	4950	1	0.25
Inc Angles	Roll	2	1600	2	0.98	2	1936	1	0.95
	Pitch	2	1600	5	0.94	2	1936	2	0.94
	Yaw offset from commanded	2	1600	7	0.99	2	1936	5	0.99