Analyzing the Relationship between Tracking and Covariance for Satellite Collision Avoidance

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INTRODUCTION

- For many years, the Earth Observing System (EOS) team as well as many other Low Earth Orbit (LEO) satellite support teams have noticed a significant reduction in covariance of secondary objects based on the amount of tracks they receive, with respect to the Time of Closest Approach (TCA) with the primary object (satellite)

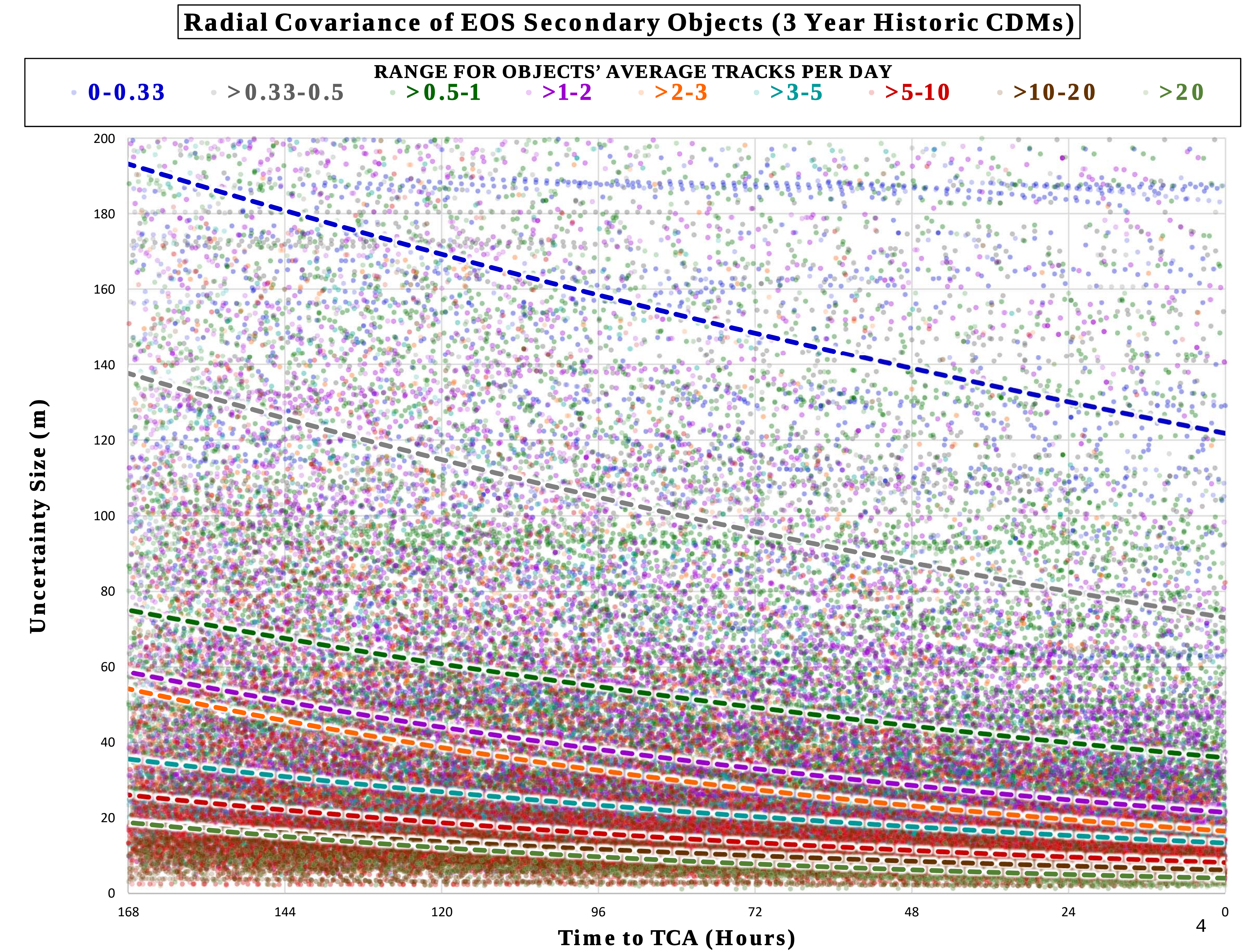
- An analysis was performed to mine the raw secondary object Conjunction Data Messages (CDMs) received for events with the EOS Aqua, Aura and Terra satellites to analyze the relationship between tracking and covariance

CDM ANALYSIS APPROACH

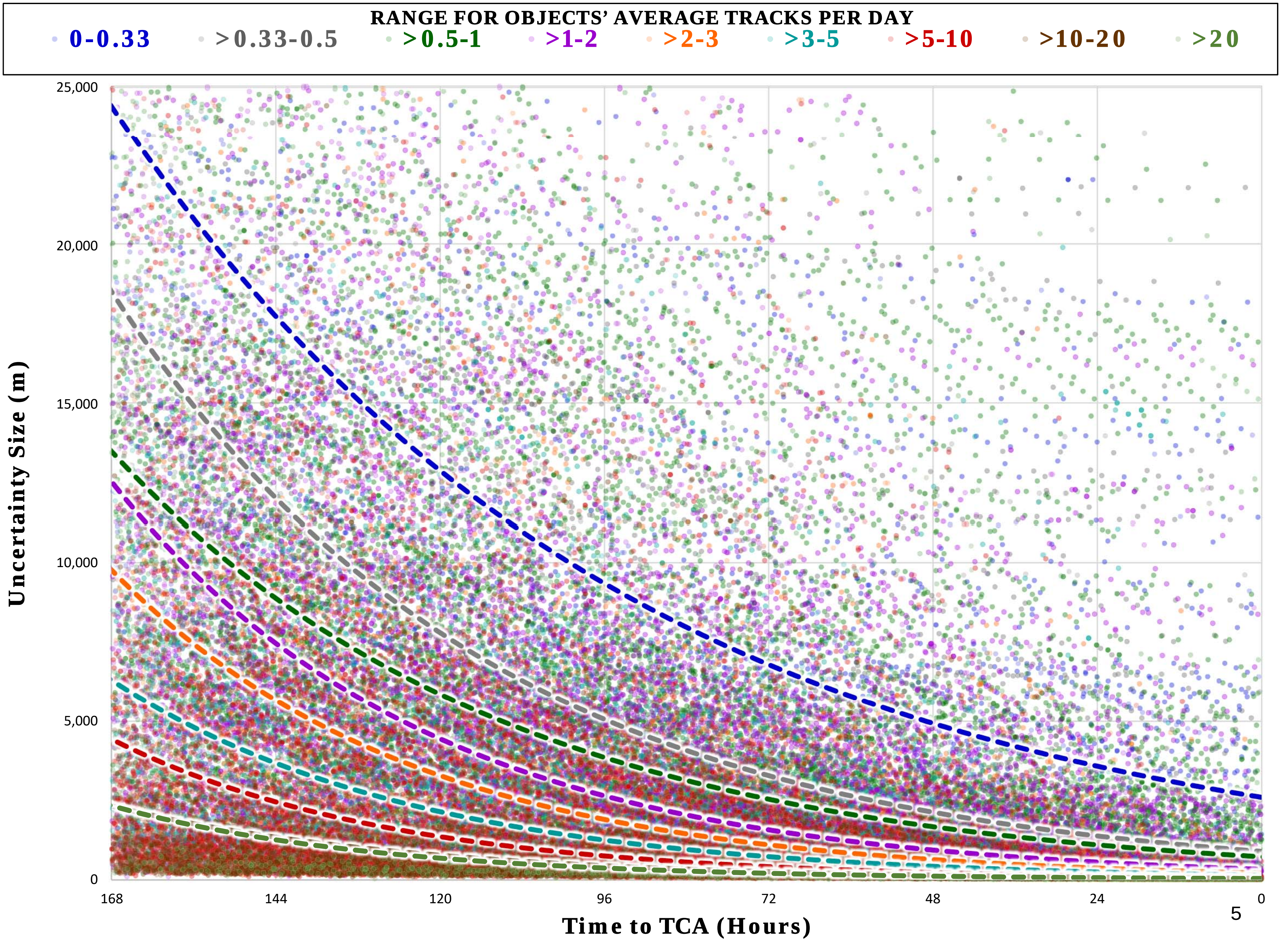
- To determine the relationship between tracking and covariance, a 3-year data set was utilized which included all CDMs (over 150,000) processed between March 2015 through February 2018 and stored at our facility by SpaceNav

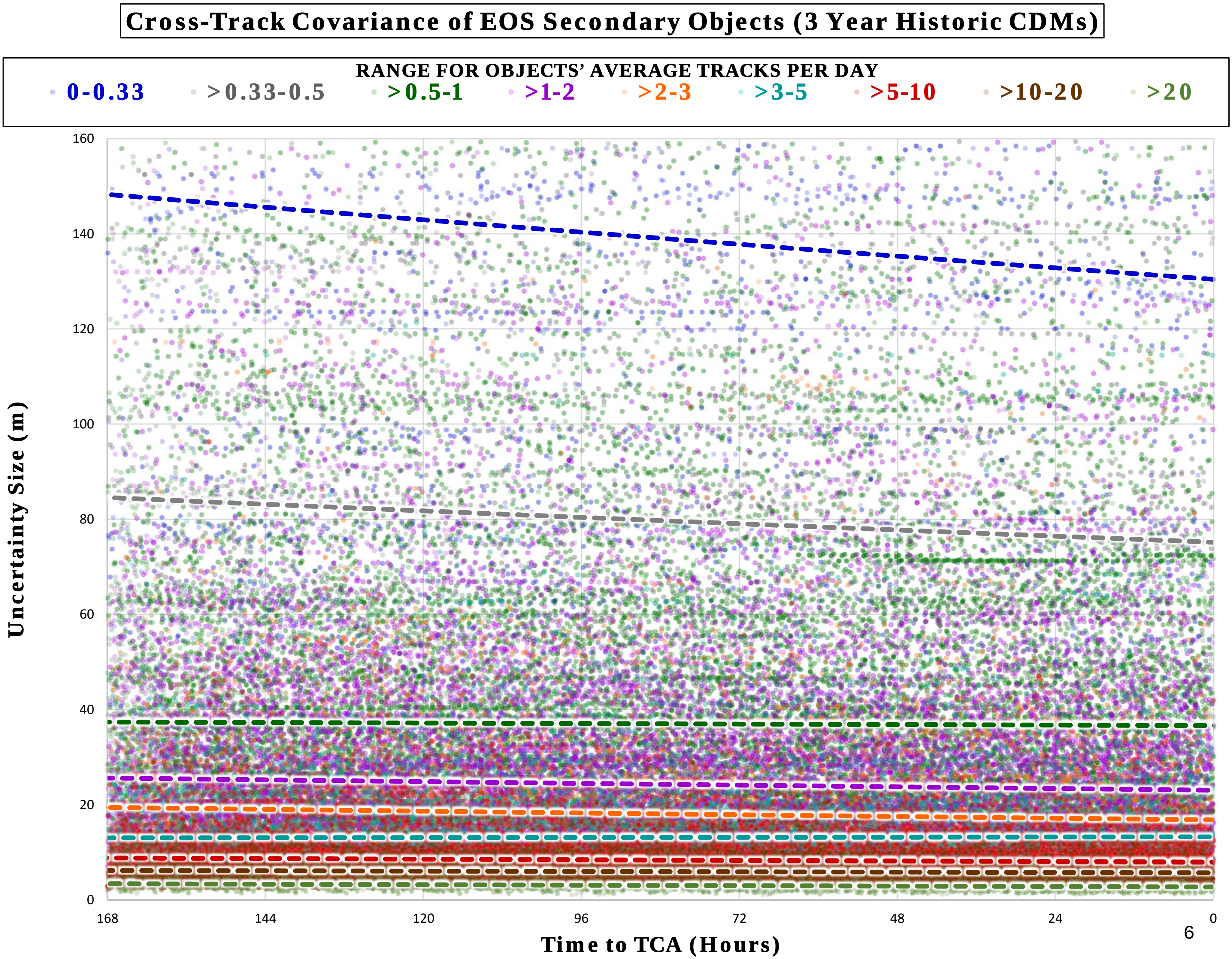
- Values of the radial, in-track, and cross-track variance values were plotted for secondary objects (along with their exponential trend lines) binned by ranges for their average tracks per day

- The plots are provided in the next few slides


Radial Covariance of EOS Secondary Objects (3 Year Historic CDMs)
RANGE FOR OBJECTS' AVERAGE TRACKS PER DAY
0-0.33
>0.33-0.5
>0.5-1
>1-2
>2-3
>3-5
>5-10
>10-20
>20
Uncertainty Size (m)
Time to TCA (Hours)
200
180
160
140
120
100
80
60
40
20
0
168
144
120
96
72
48
24
0

In-Track Covariance of EOS Secondary Objects (3 Year Historic CDMs)




Cross-Track Covariance of EOS Secondary Objects (3 Year Historic CDMs)
RANGE FOR OBJECTS' AVERAGE TRACKS PER DAY
0-0.33
>0.33-0.5
>0.5-1
>1-2
>2-3
>3-5
>5-10
>10-20
>20
Uncertainty Size (m)
160
140
120
100
80
60
40
20
0
168
144
120
96
72
48
24
0
Time to TCA (Hours)

CDM ANALYSIS RESULTS

- A direct relationship is observed for all nine tracking frequencies and all three Radial, In-track and Cross-track components, where the uncertainty values are smaller for secondary objects that have higher numbers of tracks per day
  - This indicates that the more an object is tracked, the tighter its covariance will be

- A direct relationship is also observed for all nine tracking frequencies and the Radial and In-track components, where the uncertainty values have a steeper slope for secondary objects that have fewer numbers of tracks per day
  - This indicates that the less an object is tracked, the longer it will take (as time approaches TCA) for the covariance to converge and the solution to start reaching a high level of confidence

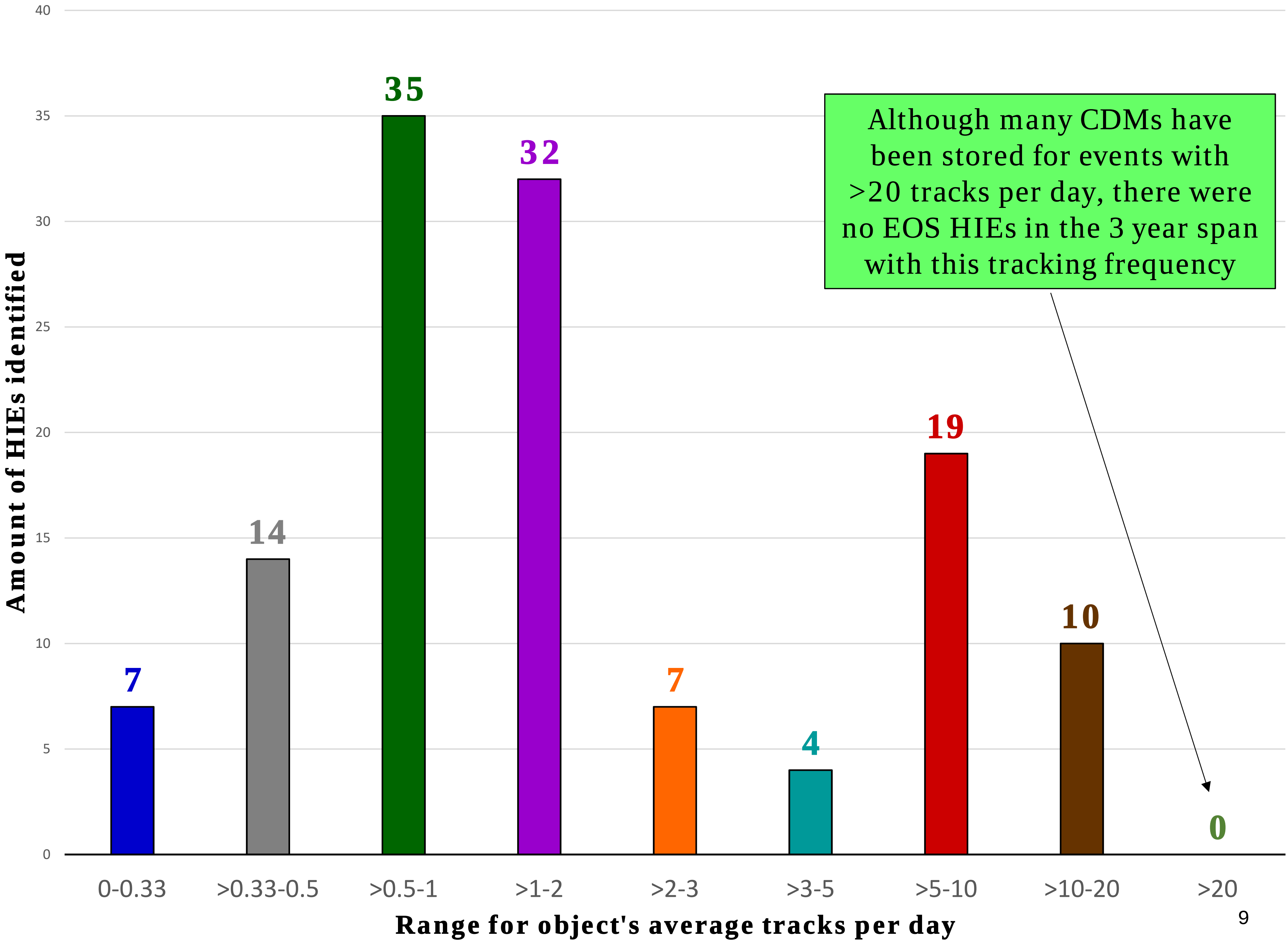
CONVERGENCE ANALYSIS

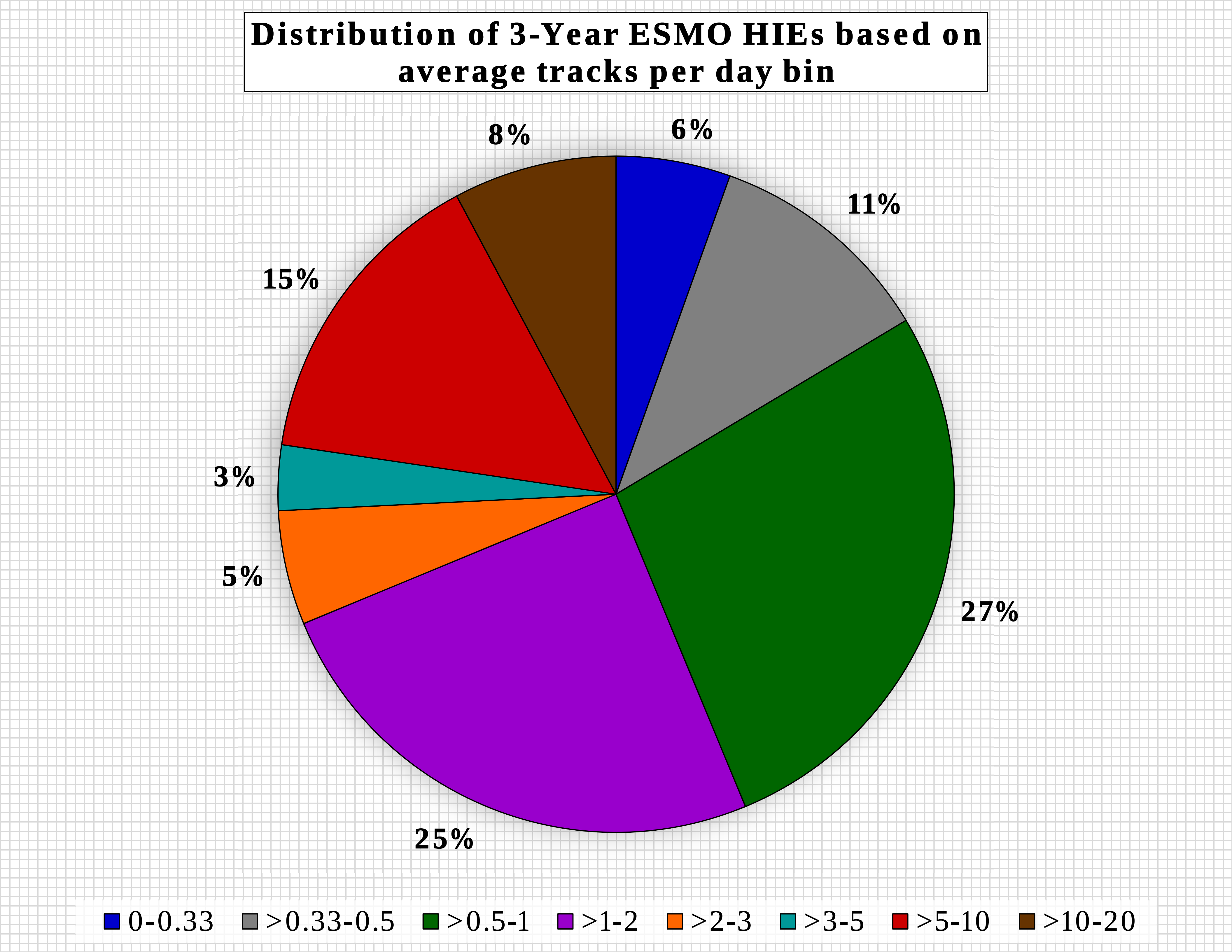
- To verify convergence of the covariance based on tracks/day, all 128 High Interest Events (HIEs) supported by EOS with some form of maneuver planning between March 2015 through February 2018 were analyzed, and an average number of tracks/day were calculated using every CDM received for the life of each event.

- The events were then classified by tracking bins which were plotted for comparison

- The plots are provided in the next two slides

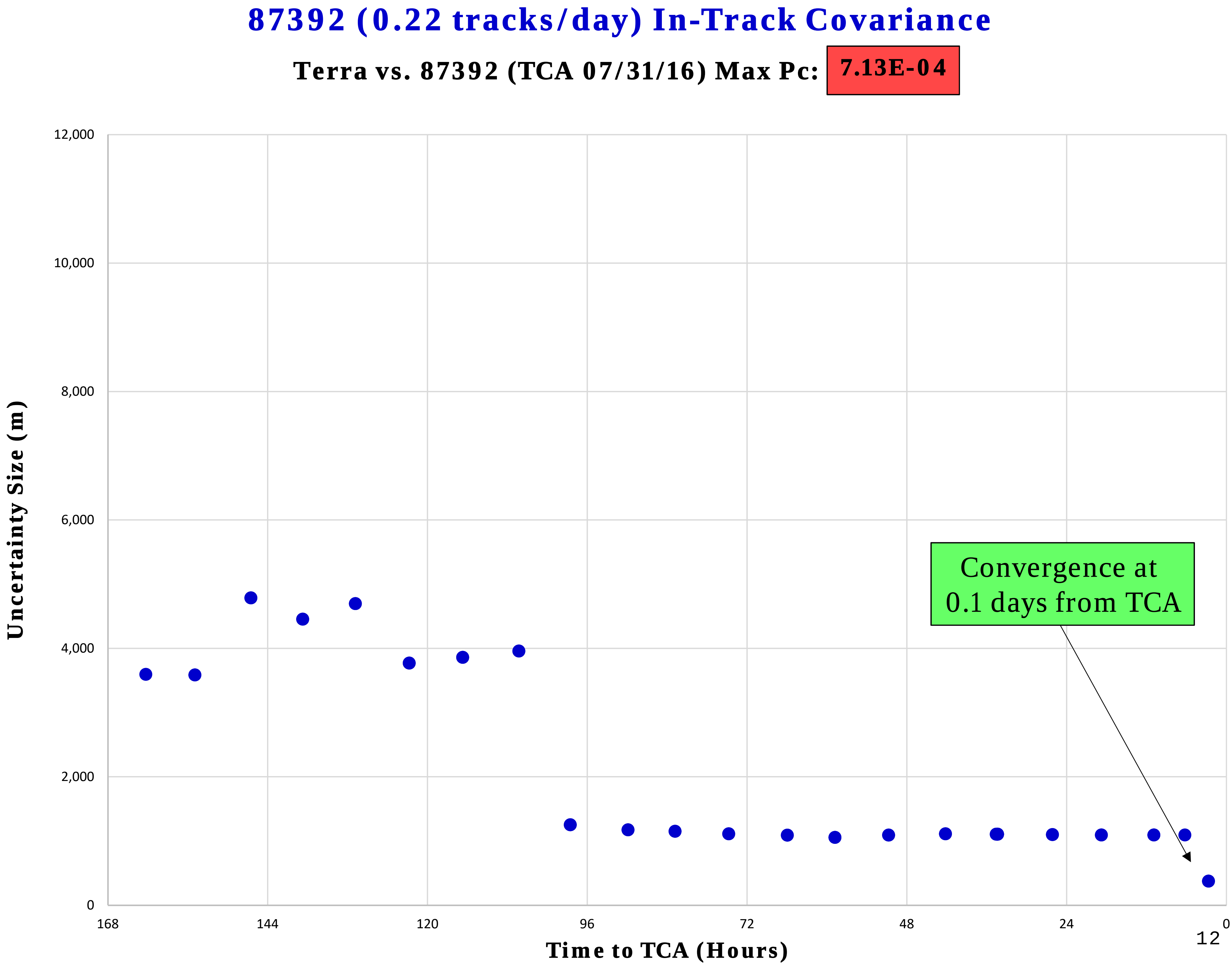
of 3-Year EOS HIEs binned by average tracks per day



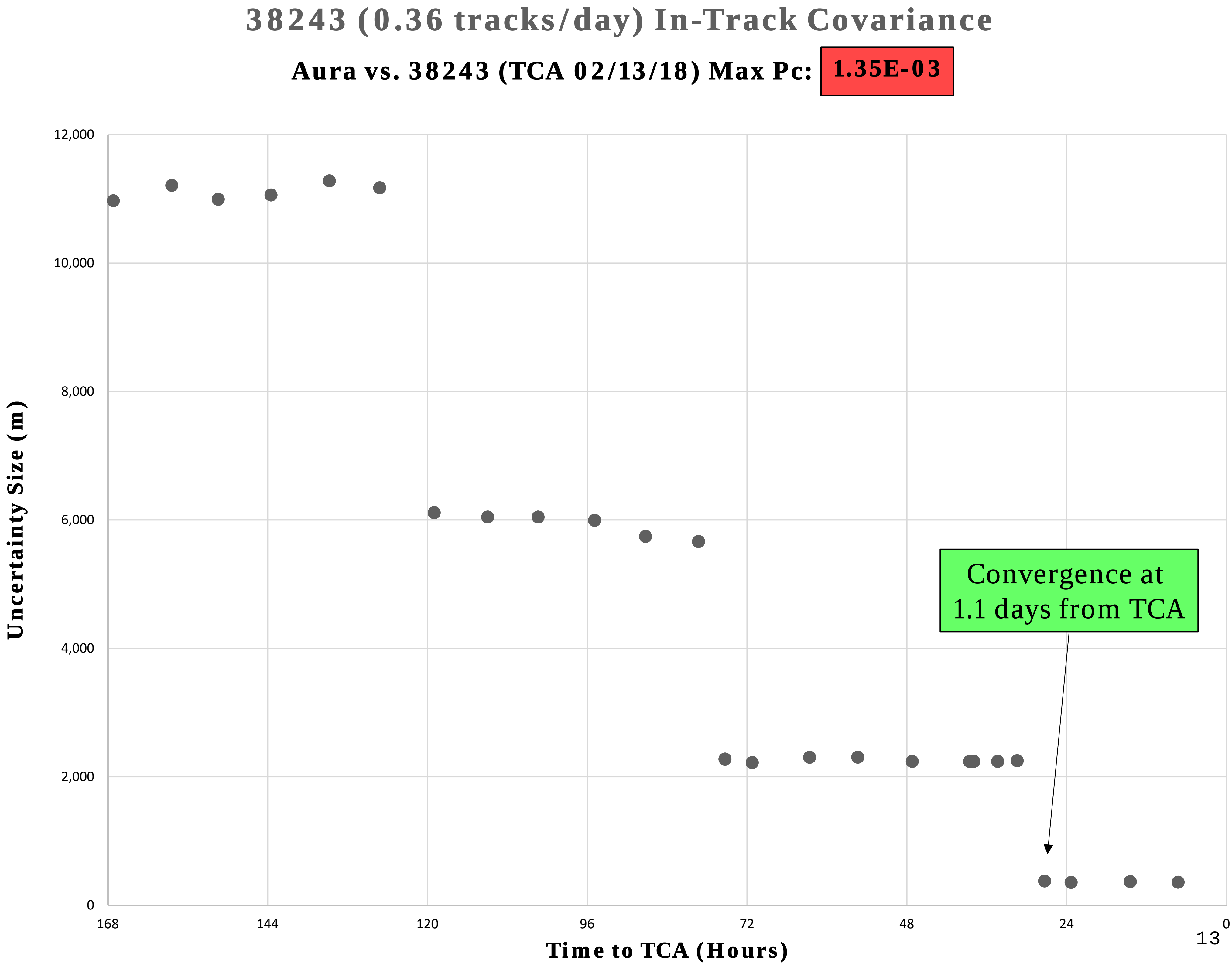

Distribution of 3-Year ESMO HIEs based on average tracks per day bin
6%
11%
27%
25%
5%
3%
15%
8%
0-0.33
>0.33-0.5
>0.5-1
>1-2
>2-3
>3-5
>5-10
>10-20

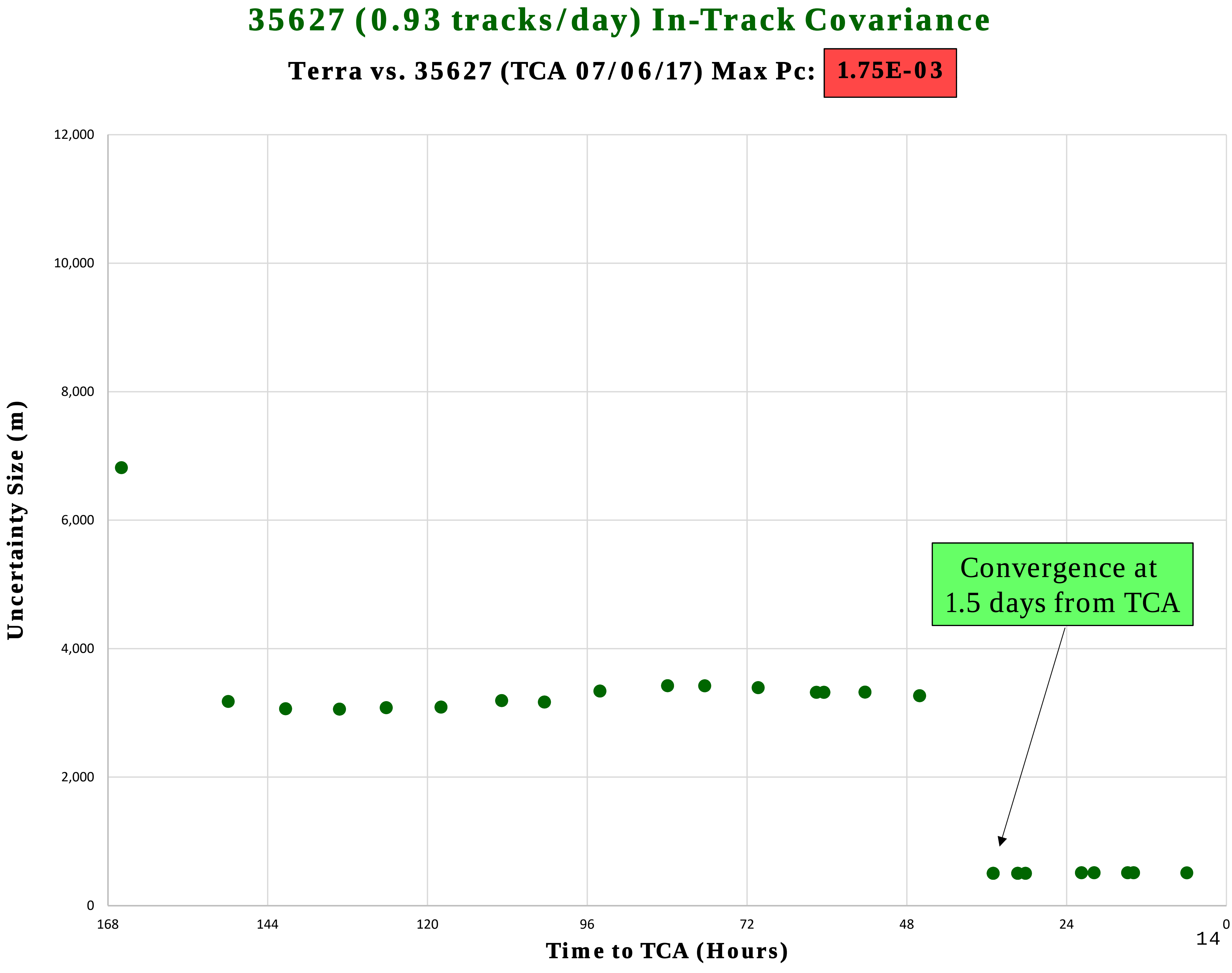
CONVERGENCE ANALYSIS (CONT'D)

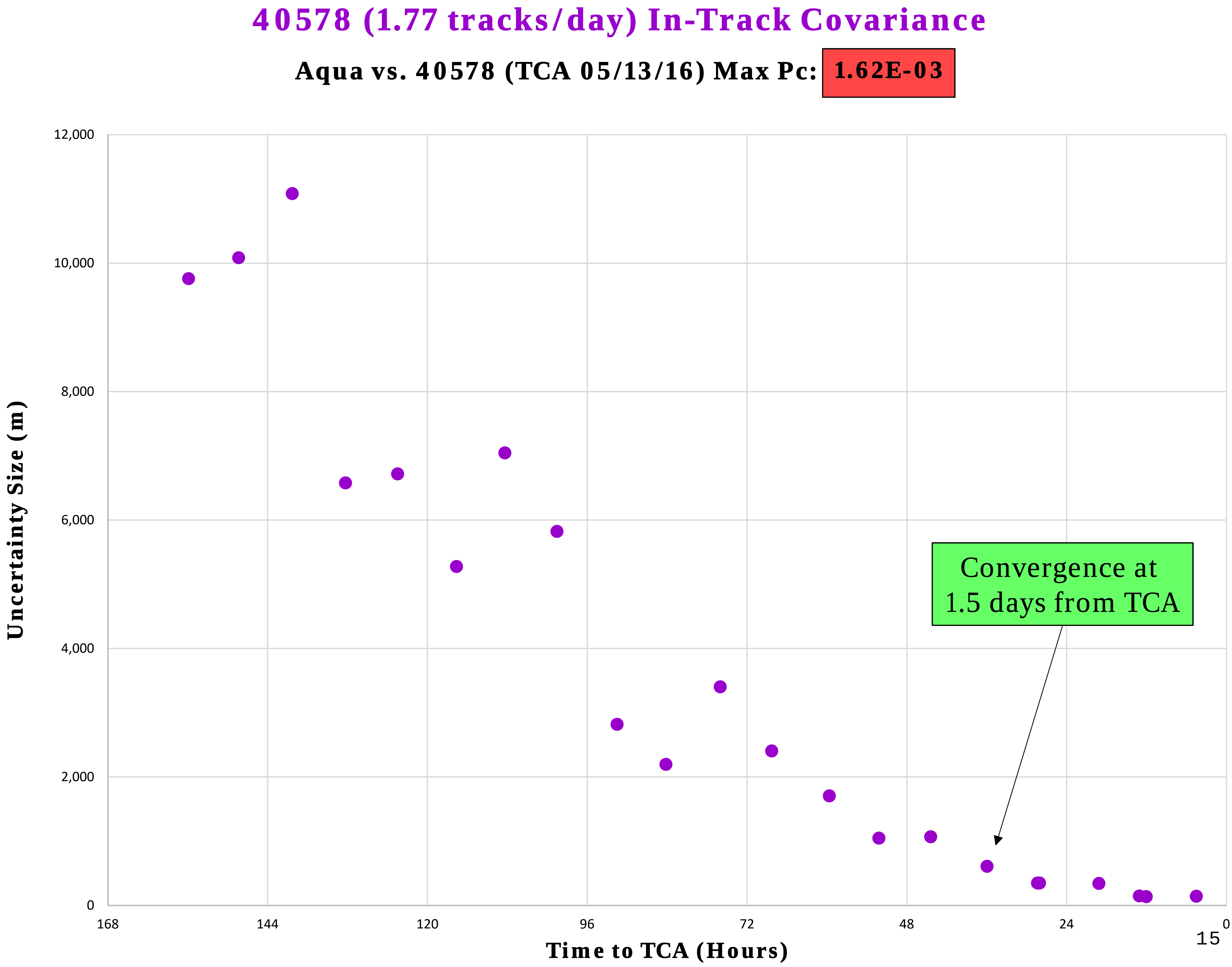
- The in-track covariance for each HIE was analyzed to further observe its relationship with its tracking bin
- To display the convergence of the covariance on an individual event level, an event which had a high Probability of Collision (Pc) and a full set of data for 7 days (stayed within the tasking volume) was selected for each tracking bin
- The in-track covariance was plotted for each of these events in the next several slides

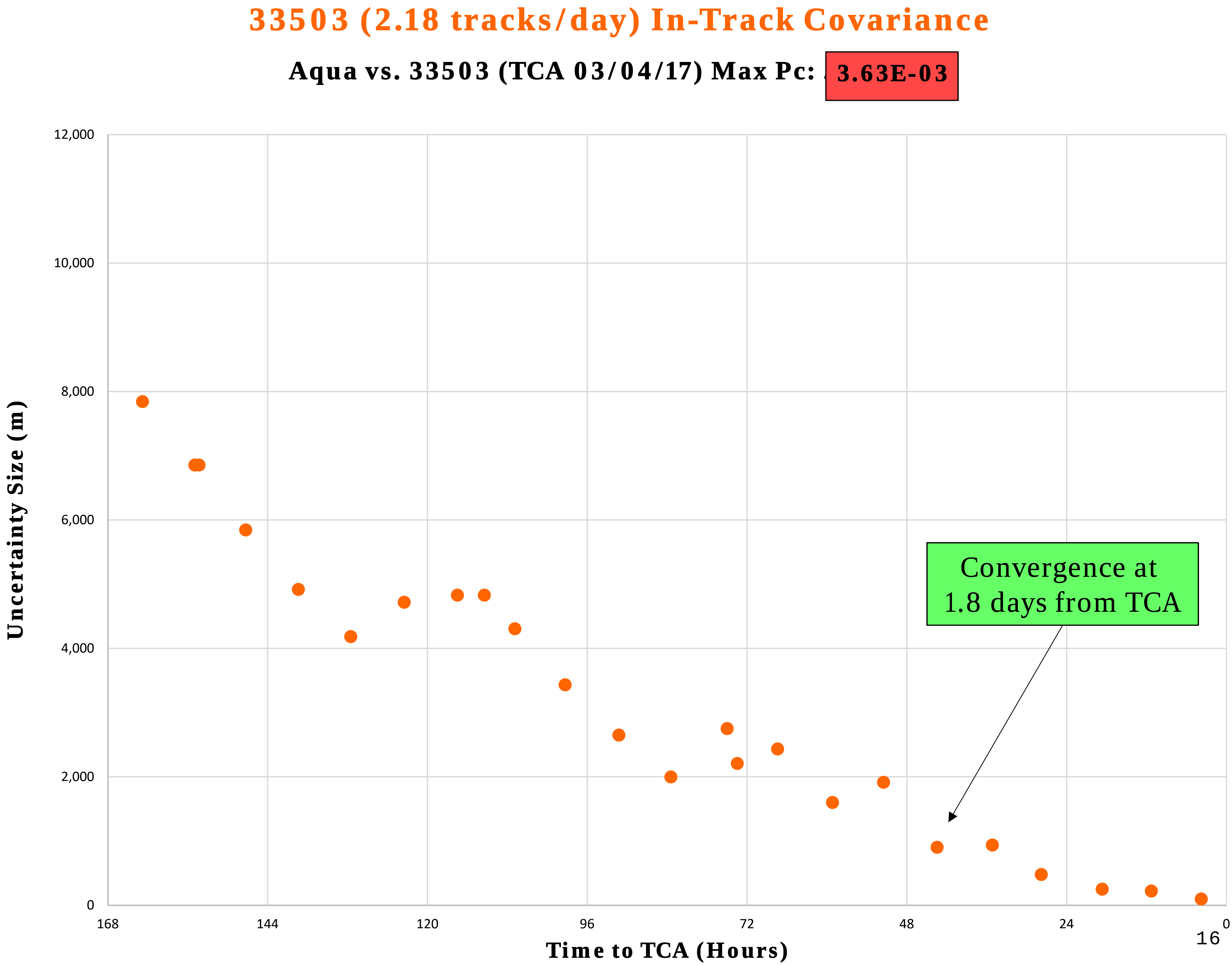


87392 (0.22 tracks/day) In-Track Covariance
Terra vs. 87392 (TCA 07/31/16) Max Pc:
7.13E-04
12,000
10,000
8,000
6,000
4,000
2,000
0
Uncertainty Size (m)
Convergence at
0.1 days from TCA
168
144
120
96
72
48
24
0
Time to TCA (Hours)

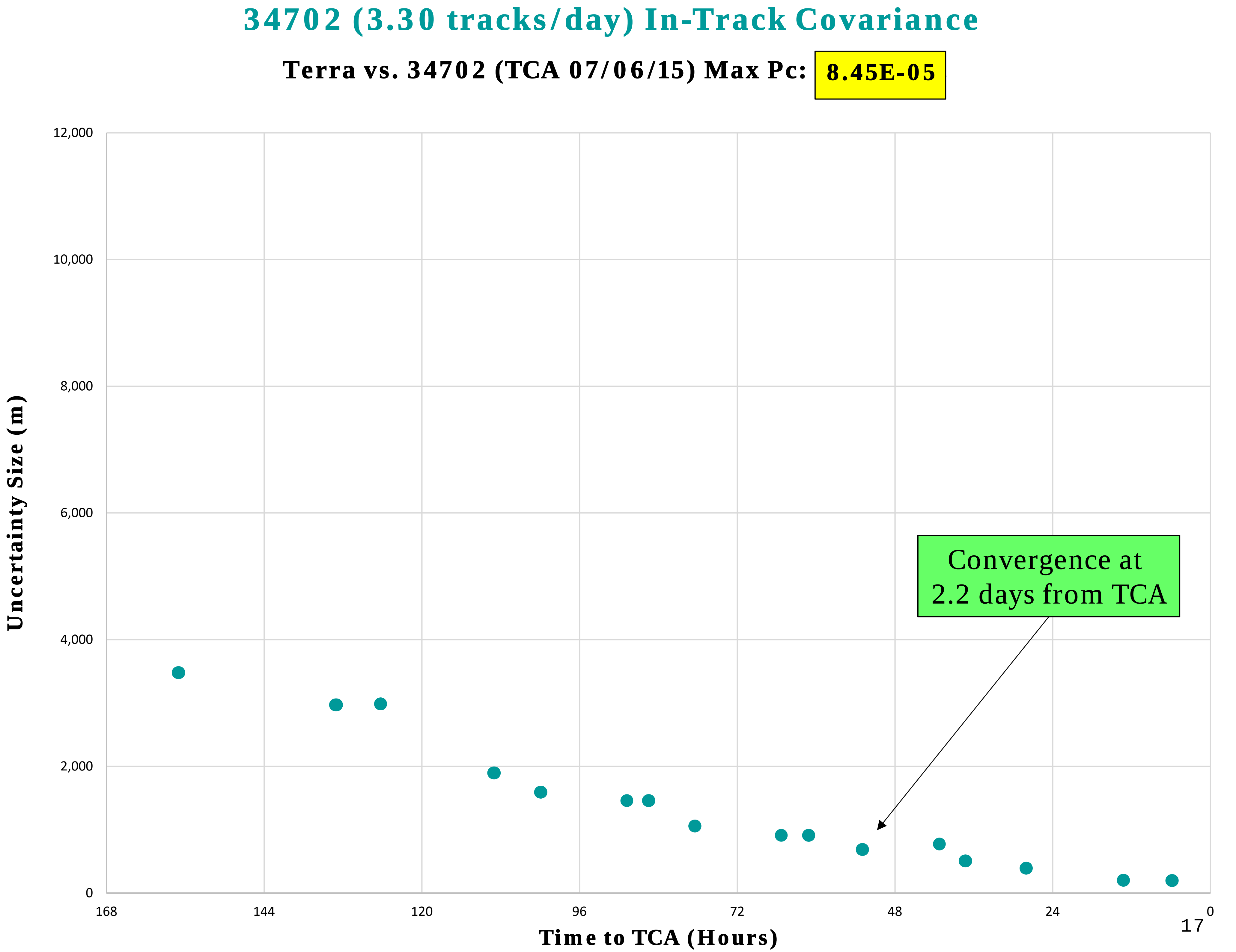

38243 (0.36 tracks/day) In-Track Covariance
Aura vs. 38243 (TCA 02/13/18) Max Pc:
1.35E-03
Uncertainty Size (m)
12,000
10,000
8,000
6,000
4,000
2,000
0
168
144
120
96
72
48
24
0
Time to TCA (Hours)
Convergence at
1.1 days from TCA


35627 (0.93 tracks/day) In-Track Covariance
Terra vs. 35627 (TCA 07/06/17) Max Pc:
1.75E-03
Uncertainty Size (m)
12,000
10,000
8,000
6,000
4,000
2,000
0
168
144
120
96
72
48
24
0
Time to TCA (Hours)
Convergence at
1.5 days from TCA


40578 (1.77 tracks/day) In-Track Covariance
Aqua vs. 40578 (TCA 05/13/16) Max Pc: 1.62E-03
Uncertainty Size (m)
12,000
10,000
8,000
6,000
4,000
2,000
0
168
144
120
96
72
48
24
0
Time to TCA (Hours)
Convergence at 1.5 days from TCA

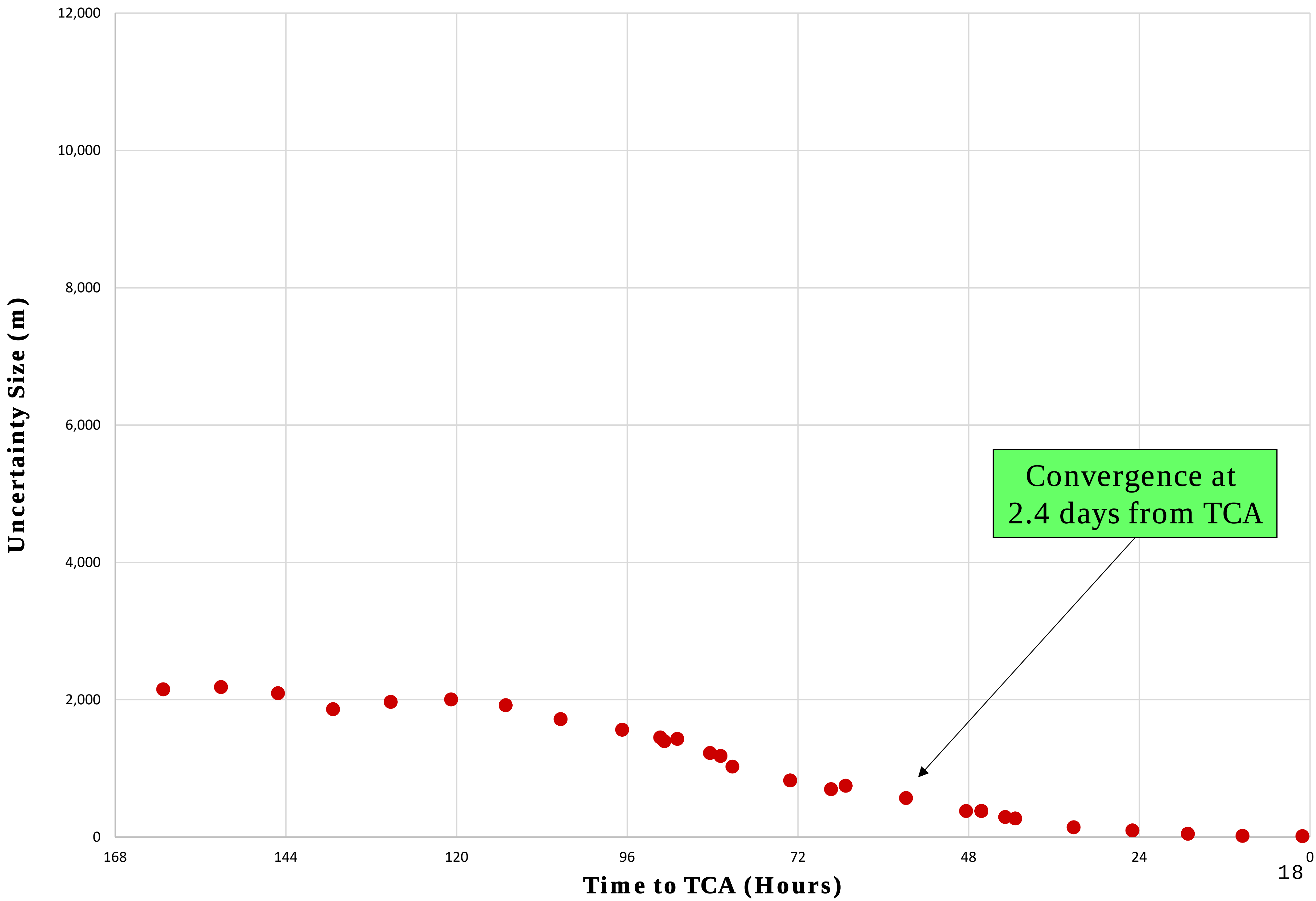


33503 (2.18 tracks/day) In-Track Covariance
Aqua vs. 33503 (TCA 03/04/17) Max Pc:
3.63E-03
Uncertainty Size (m)
12,000
10,000
8,000
6,000
4,000
2,000
0
168
144
120
96
72
48
24
0
Time to TCA (Hours)
Convergence at
1.8 days from TCA


34702 (3.30 tracks/day) In-Track Covariance
Terra vs. 34702 (TCA 07/06/15) Max Pc: 8.45E-05
12,000
10,000
8,000
6,000
4,000
2,000
0
Uncertainty Size (m)
Convergence at 2.2 days from TCA
168
144
120
96
72
48
24
0
Time to TCA (Hours)

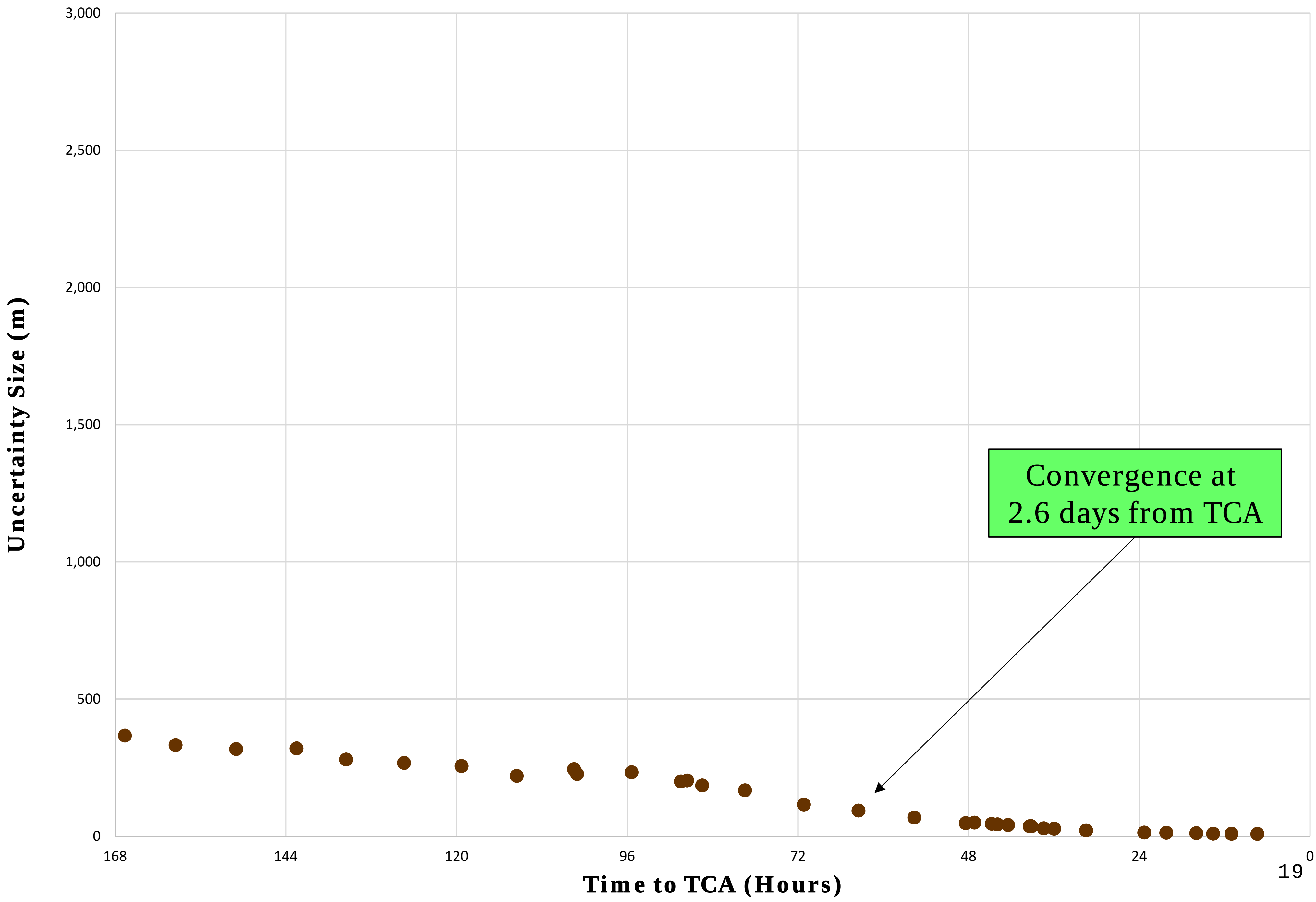
26294 (8.25 tracks/day) In-Track Covariance

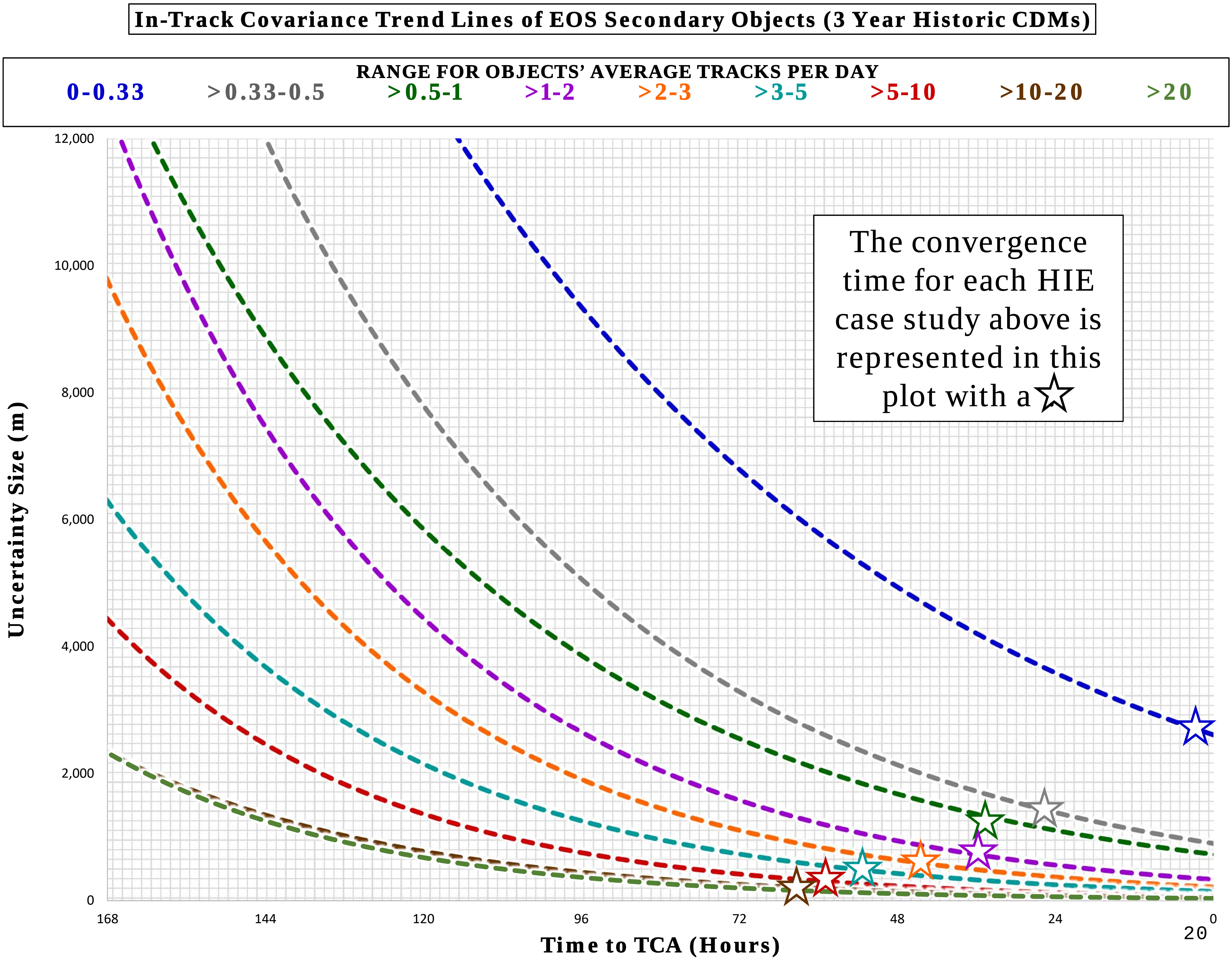
Aqua vs. 26294 (TCA 10/16/17) Max Pc: 3.70E-02



25759 (18.88 tracks/day) In-Track Covariance

Aura vs. 25759 (TCA 03/26/17) Max Pc: 3.45E-02




In-Track Covariance Trend Lines of EOS Secondary Objects (3 Year Historic CDMs)
RANGE FOR OBJECTS' AVERAGE TRACKS PER DAY
0-0.33
>0.33-0.5
>0.5-1
>1-2
>2-3
>3-5
>5-10
>10-20
>20
The convergence time for each HIE case study above is represented in this plot with a ☆
Uncertainty Size (m)
12,000
10,000
8,000
6,000
4,000
2,000
0
168
144
120
96
72
48
24
0
Time to TCA (Hours)

CONVERGENCE ANALYSIS RESULTS

- After analyzing the data in these plots we detect a very noticeable relation, that the more tracks a secondary object receives a day, the higher the chance is that the covariance will converge to a stable value further from TCA

- Based on these results, we deduce some approximate times for which we can expect the in-track covariance to reach a convergence point, and thus the Pc to reach a value of confidence

- A few of the HIE case studies are compared to actual operational Pc values, as represented in the following plots

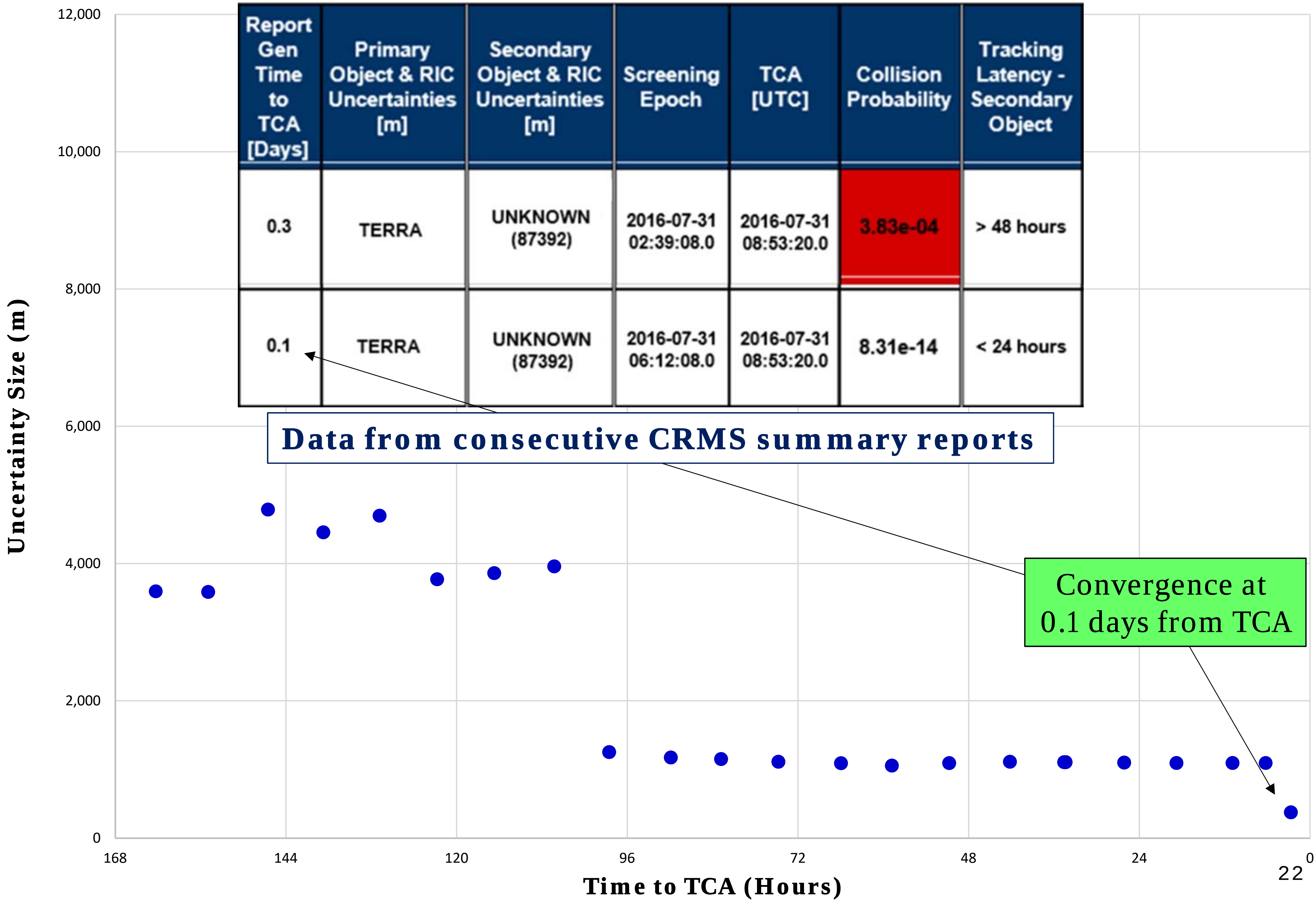
- The Pc values and supplemental information were extracted from summary reports produced by the Collision Risk Mitigation System (CRMS) used for EOS and developed by SpaceNav

87392 (0.22 tracks/day) In-Track Covariance

Terra vs. 87392 (TCA 07/31/16) Max Pc: 7.13E-04

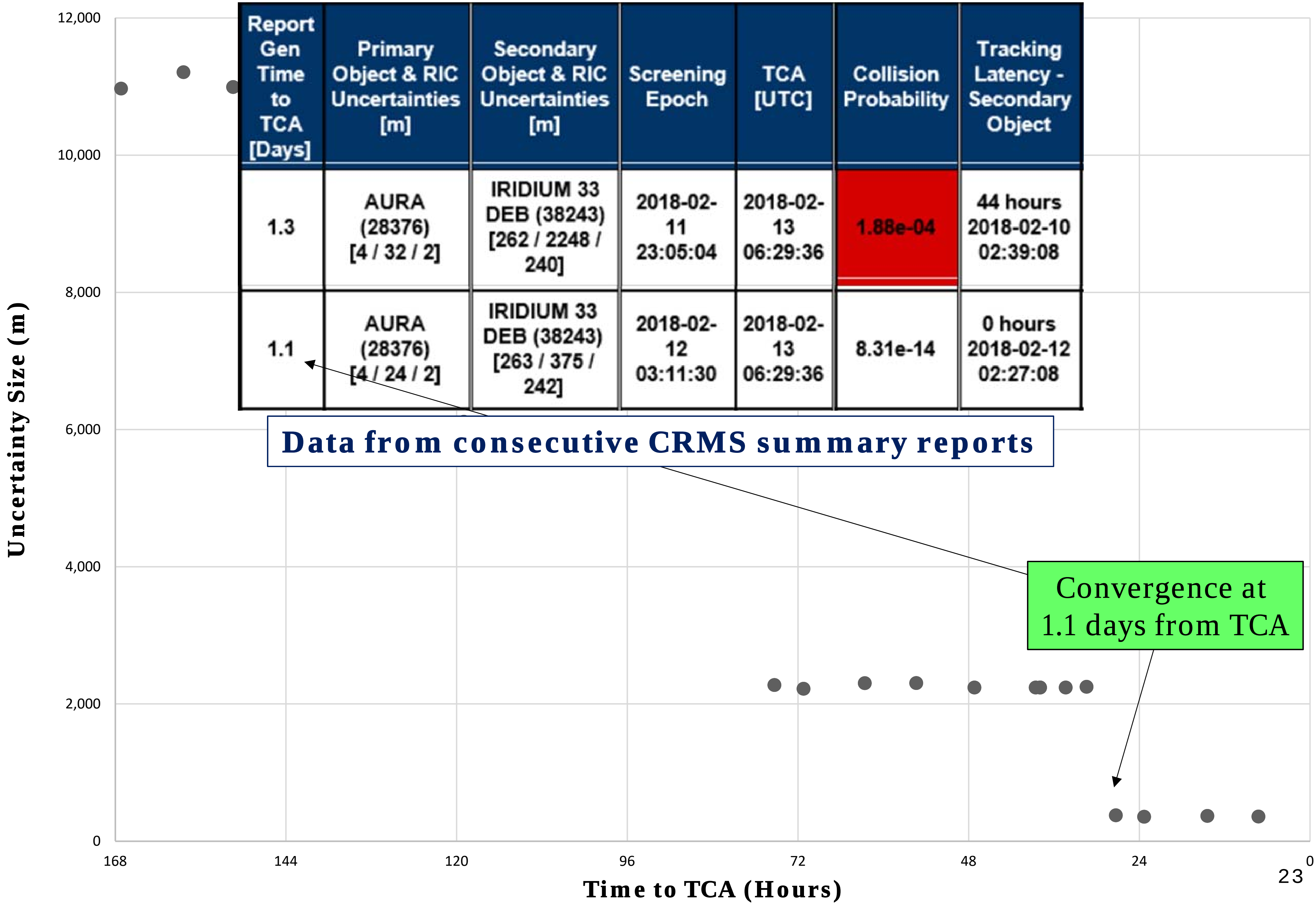
Report Gen Time to TCA [Days]	Primary Object & RIC Uncertainties [m]	Secondary Object & RIC Uncertainties [m]	Screening Epoch	TCA [UTC]	Collision Probability	Tracking Latency - Secondary Object
0.3	TERRA	UNKNOWN (87392)	2016-07-31 02:39:08.0	2016-07-31 08:53:20.0	3.83e-04	> 48 hours
0.1	TERRA	UNKNOWN (87392)	2016-07-31 06:12:08.0	2016-07-31 08:53:20.0	8.31e-14	< 24 hours

Data from consecutive CRMS summary reports



38243 (0.36 tracks/day) In-Track Covariance

Aura vs. 38243 (TCA 02/13/18) Max Pc: 1.35E-03

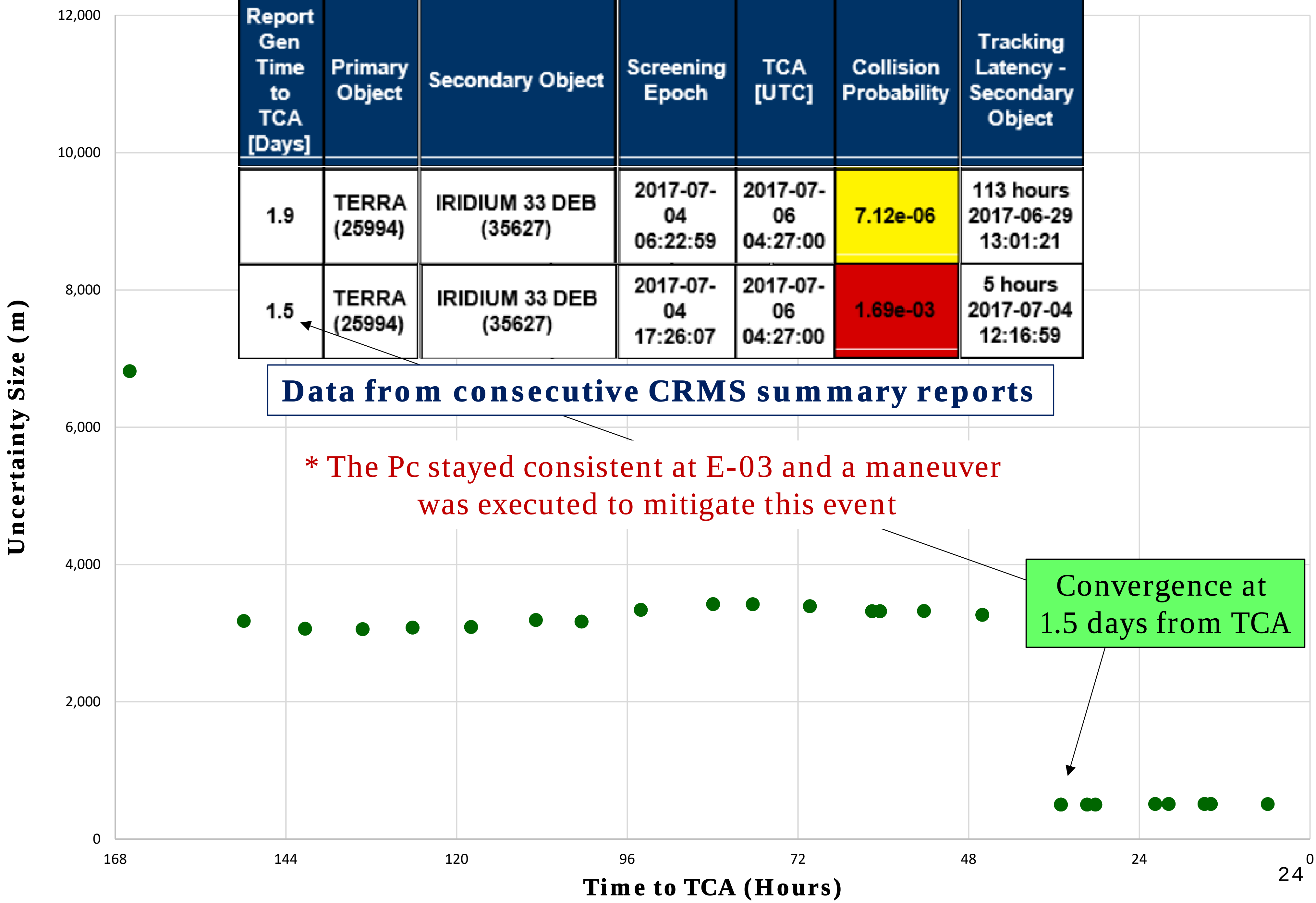


Report Gen Time to TCA [Days]	Primary Object & RIC Uncertainties [m]	Secondary Object & RIC Uncertainties [m]	Screening Epoch	TCA [UTC]	Collision Probability	Tracking Latency - Secondary Object
1.3	AURA (28376) [4 / 32 / 2]	IRIDIUM 33 DEB (38243) [262 / 2248 / 240]	2018-02-11 23:05:04	2018-02-13 06:29:36	1.88e-04	44 hours 2018-02-10 02:39:08
1.1	AURA (28376) [4 / 24 / 2]	IRIDIUM 33 DEB (38243) [263 / 375 / 242]	2018-02-12 03:11:30	2018-02-13 06:29:36	8.31e-14	0 hours 2018-02-12 02:27:08

35627 (0.93 tracks/day) In-Track Covariance

Terra vs. 35627 (TCA 07/06/17) Max Pc: 1.75E-03

Report Gen Time to TCA [Days]	Primary Object	Secondary Object	Screening Epoch	TCA [UTC]	Collision Probability	Tracking Latency - Secondary Object
1.9	TERRA (25994)	IRIDIUM 33 DEB (35627)	2017-07-04 06:22:59	2017-07-06 04:27:00	7.12e-06	113 hours 2017-06-29 13:01:21
1.5	TERRA (25994)	IRIDIUM 33 DEB (35627)	2017-07-04 17:26:07	2017-07-06 04:27:00	1.69e-03	5 hours 2017-07-04 12:16:59

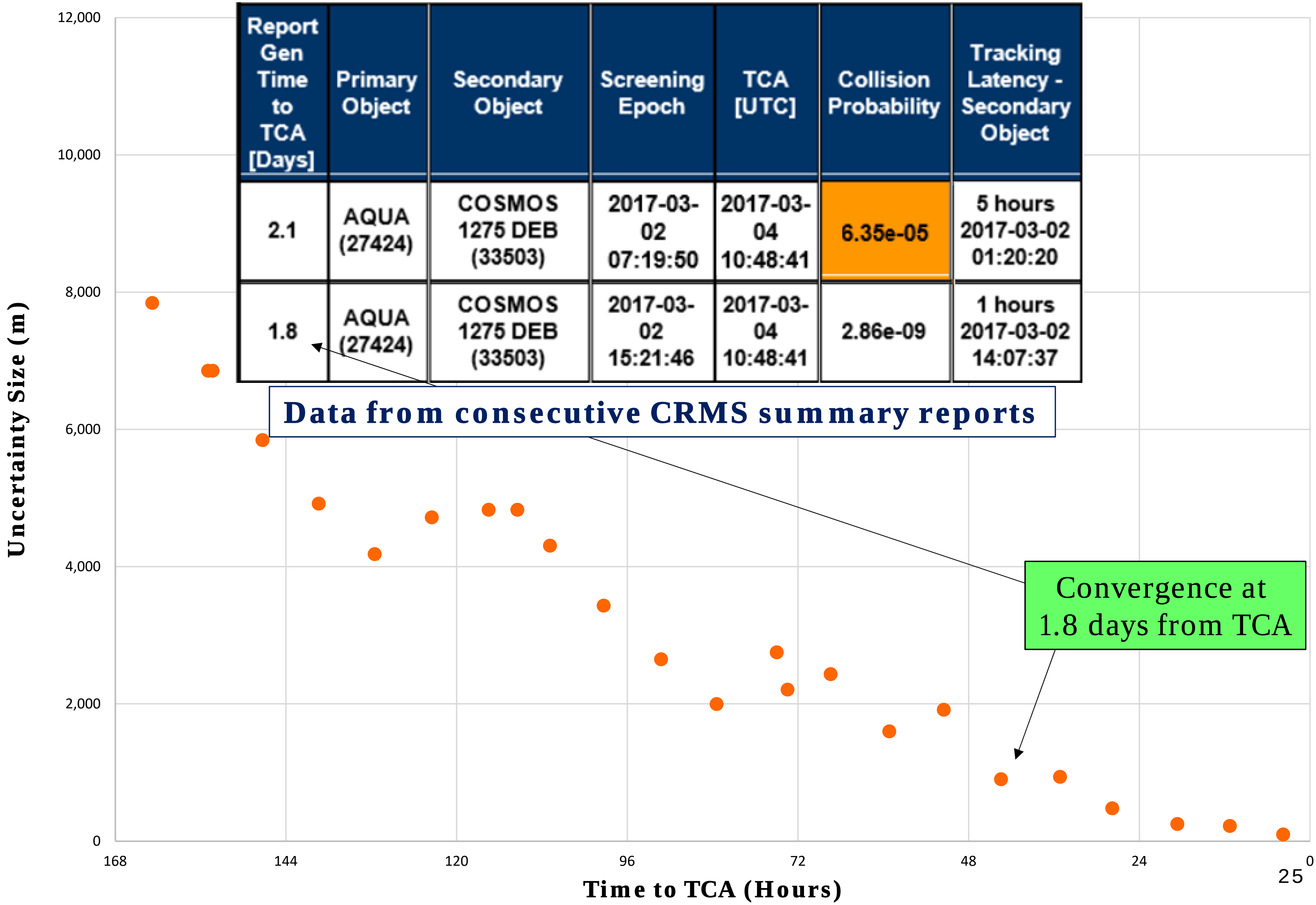


33503 (2.18 tracks/day) In-Track Covariance

Aqua vs. 33503 (TCA 03/04/17) Max Pc: 3.63E-03

Report Gen Time to TCA [Days]	Primary Object	Secondary Object	Screening Epoch	TCA [UTC]	Collision Probability	Tracking Latency - Secondary Object
2.1	AQUA (27424)	COSMOS 1275 DEB (33503)	2017-03-02 07:19:50	2017-03-04 10:48:41	6.35e-05	5 hours 2017-03-02 01:20:20
1.8	AQUA (27424)	COSMOS 1275 DEB (33503)	2017-03-02 15:21:46	2017-03-04 10:48:41	2.86e-09	1 hours 2017-03-02 14:07:37

Data from consecutive CRMS summary reports



FINAL OBSERVATIONS

- After parsing through all of the data and examining the plots, the following was observed:
  - The more tracks a secondary object receives a day, it is more likely that the covariance will converge earlier in time in relation to it's TCA with the primary
  - There appears to be an empirical relationship between how much an object is tracked, and the actual time from TCA that covariance convergence takes place
  - There appears to be a correlation between when covariance convergence takes place and when the Pc for an event reaches a confident level
- Note: Hundreds of additional events will have to be analyzed to confirm these statements

FUTURE WORK

- Analyze many more events and attempt to develop a sophisticated algorithm which can provide Low Earth Orbit (LEO) Owner Operators with verified and valid expectations for when a High Interest Event can be expected to reach a confident Pc level, based on its tracking.

- Include both radial and in-track covariance as well as approach angle geometry data into the analysis if needed.

- Take advantage of the additional CDMs retrieved once the space fence begins tracking, which can be utilized for analysis to achieve more accurate results.

- Note: With the upcoming space fence, more benefit can be gained by utilizing this knowledge, as the increase of secondary objects and additional data uncertainty may possibly make maneuver planning very overwhelming