MIT International Center for Air Transportation

# A Commercial Space Operator Cost Model for Analyzing Airspace Launch Equity

Sponsored by the FAA's
National Center of Excellence for Aviation Operations Research (NEXTOR)

**Greg O'Neill**
*Postdoctoral Associate*
Massachusetts Institute of Technology
(mgoneill@mit.edu)

**John Hansman**
*Professor*
Massachusetts Institute of Technology
(rjhans@mit.edu)

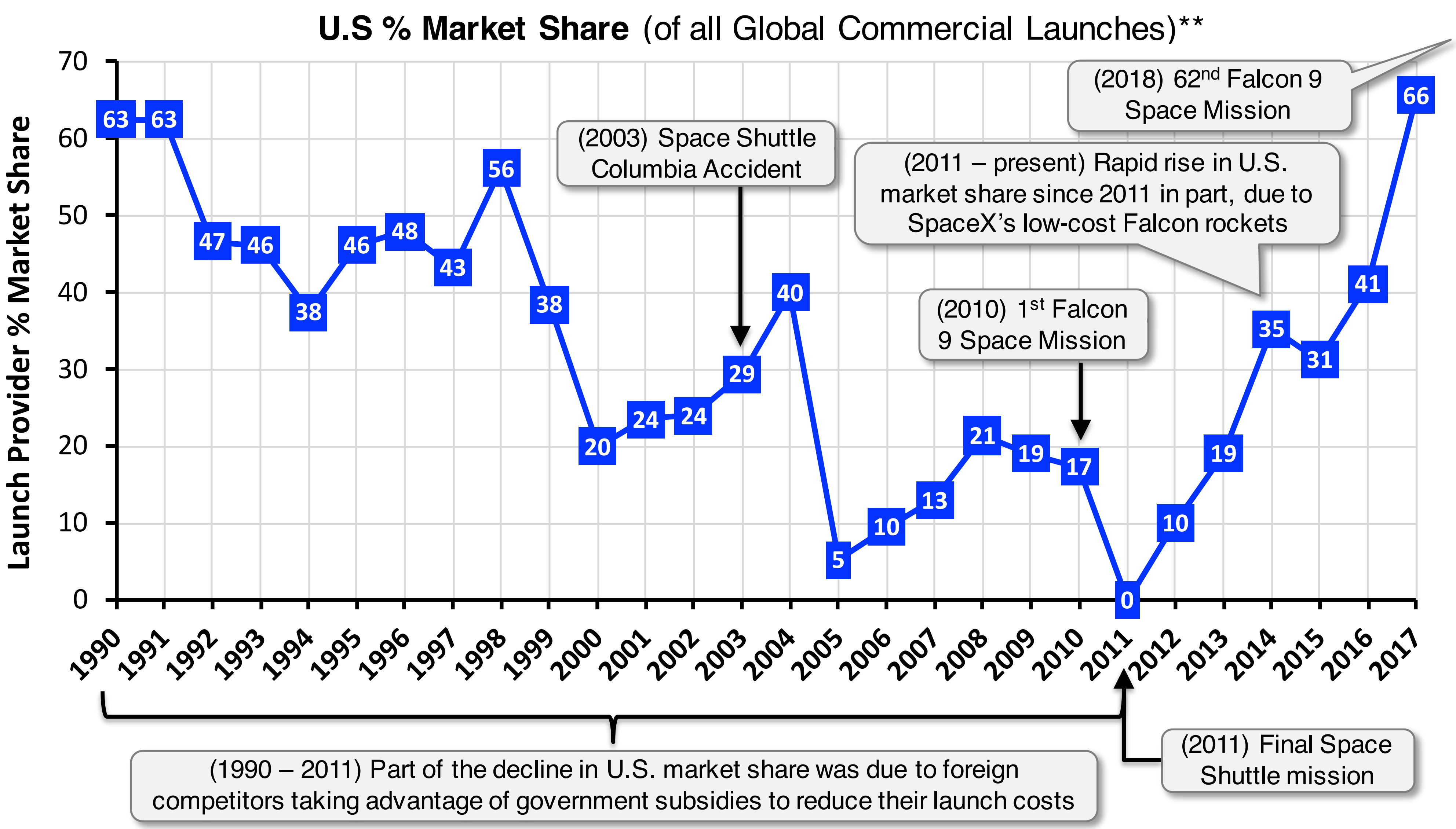
**Technical Monitors:** Thea Graham, Sally Frodge, and Marcos Bolanos

**NEXTRO II Research Symposium**
October 26, 2018

*All data and results are preliminary and subject to change*

# Growth in U.S. Commercial Space Launches

- The U.S. has seen a significant increase in commercial launches since 2011*

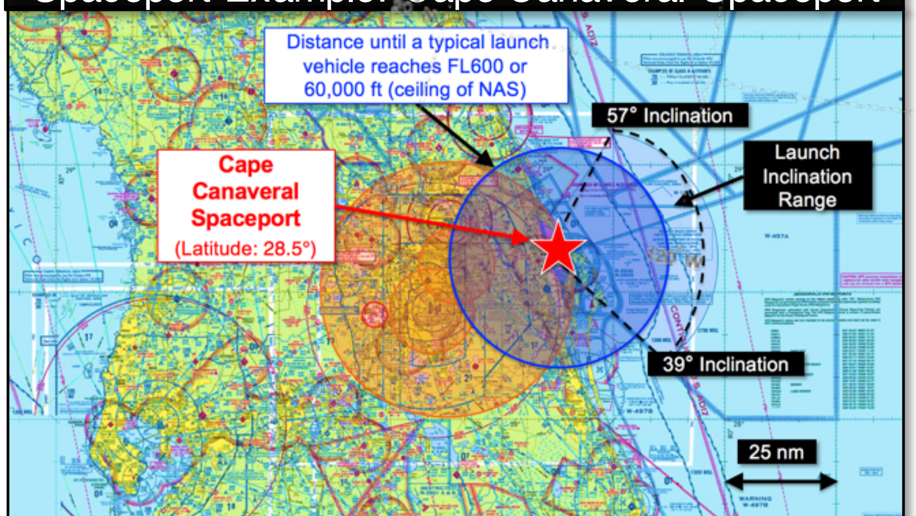



*A commercial launch is a launch that is internationally competed or FAA-licensed, or privately financed (The Annual Compendium of Commercial Space Transportation, 2016-2017).
** U.S. launches exclude NASA ISS cargo resupply missions because they are not internationally competed launch contracts as well as Sea Launches.

MIT ICAT

# Growth in U.S. Commercial Spaceports & Launch Facilities


Spaceport Example: Cape Canaveral Spaceport




- 7 of the 12 current FAA-licensed launch sites and spaceports were developed after 2000

# New and Emerging Commercial Space Vehicles

## (1) Launch Vehicles

SpaceX's Falcon 9


Orbital

Blue Origin's New Shepard


Sub-orbital

## (2) Payloads

EUTELSAT 172B telecommunications satellite

GeoEye-1 Earth Imaging Satellite


## (3) Flight Vehicles

Virgin Galactic's SpaceShipTwo & White Knight Two


SpaceX's Dragon Orbit Transfer Vehicle

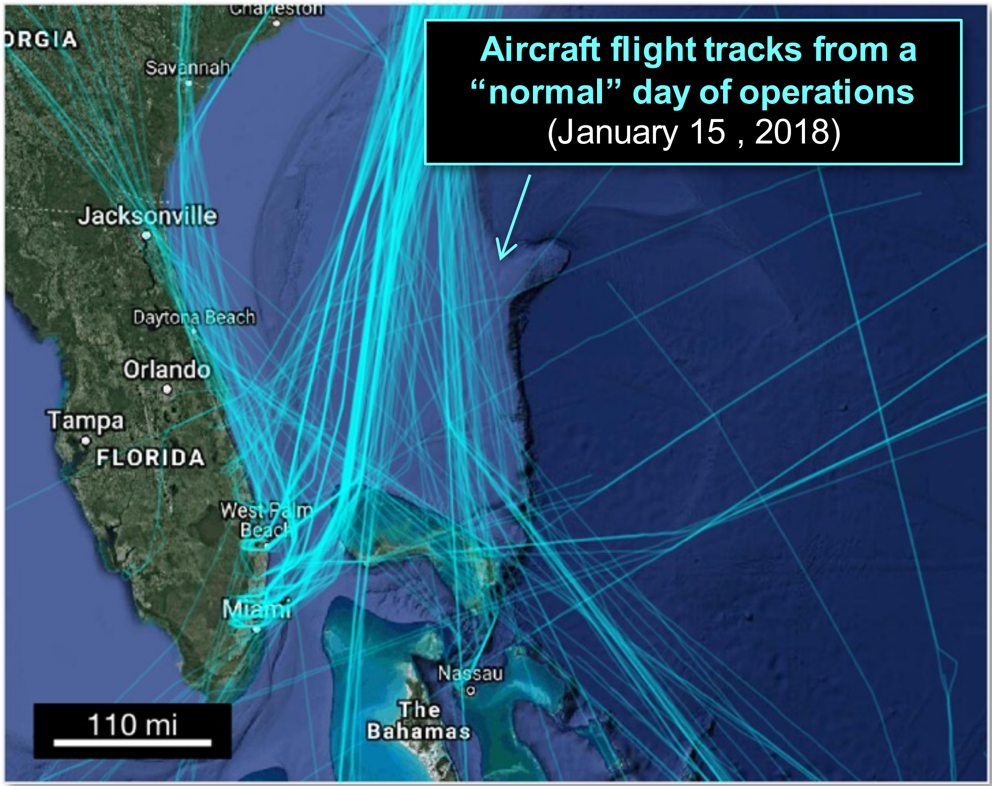

Sierra Nevada Corporation's Dream Chaser

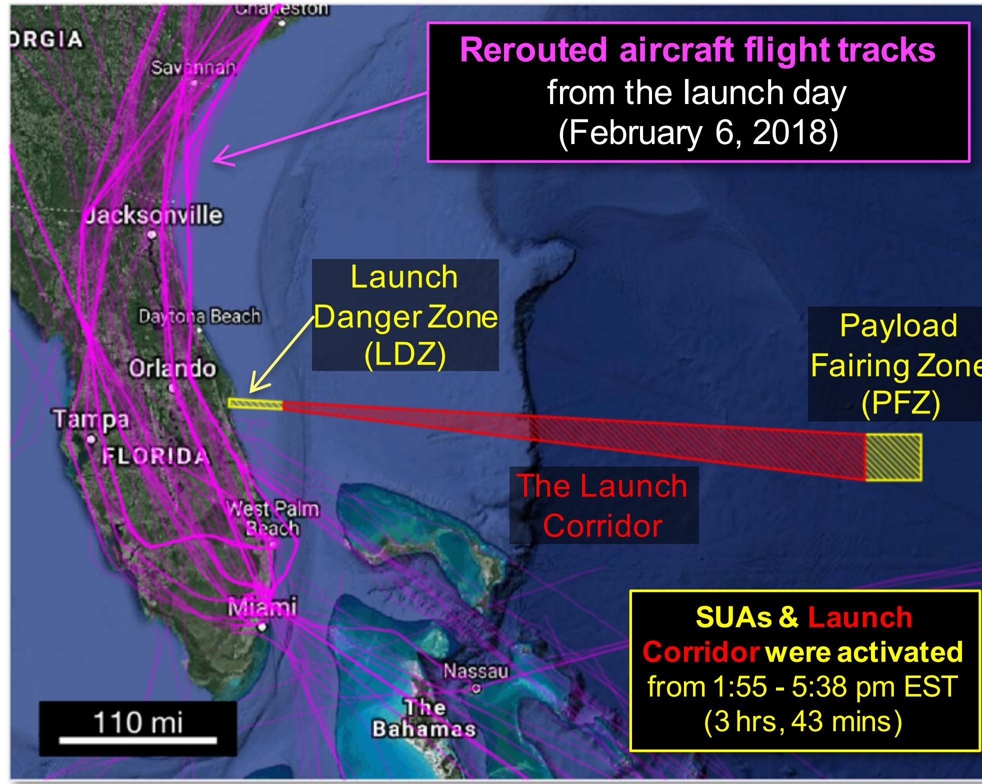

- There is no open-source cost model for these three classes space vehicles and their operations

# Preliminary Aircraft Rerouting Impact Analysis for the 2018 Falcon Heavy Launch*

→ Approximately 338 aircraft were rerouted for the Falcon Heavy launch at Cape Canaveral

→ On average, the operating cost of each rerouted aircraft increased by about $293




| Impact Metrics | **Total Δ Impact** (all rerouted aircraft) | **Average Δ Impact** (per rerouted aircraft) |
|---|---|---|
| Flight Path | +26,766 nm | +79.19 nm |
| Fuel | +78,555 gals | +232.41 gals |
| Flight Time | +53.53 hrs | +9 mins, 30 secs |
| Reroute Cost | +$99,033 | +$293.00 |

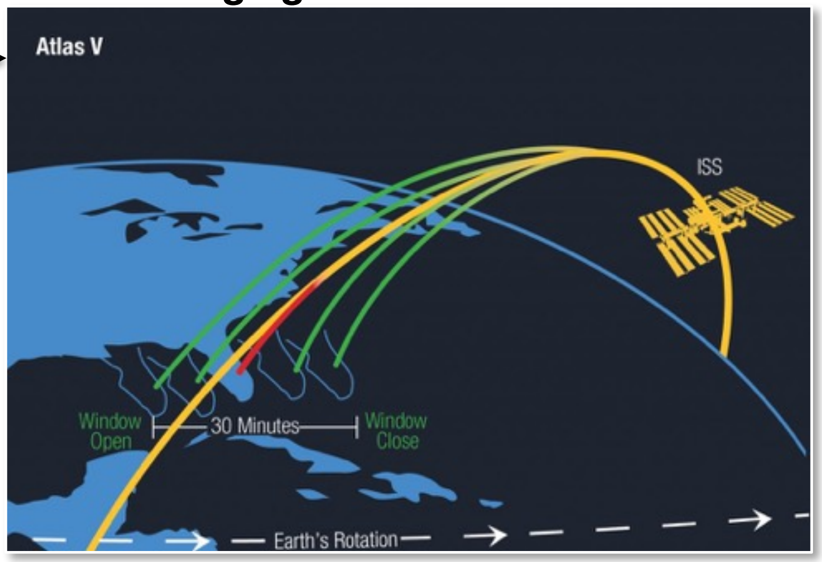
$$\Delta \text{ Impact} = \text{Impact}_{\text{Launch Day}} - \text{Impact}_{\text{"Normal" Day}}$$

** Analysis done using FAA TFMS flight data and a custom aircraft performance model*

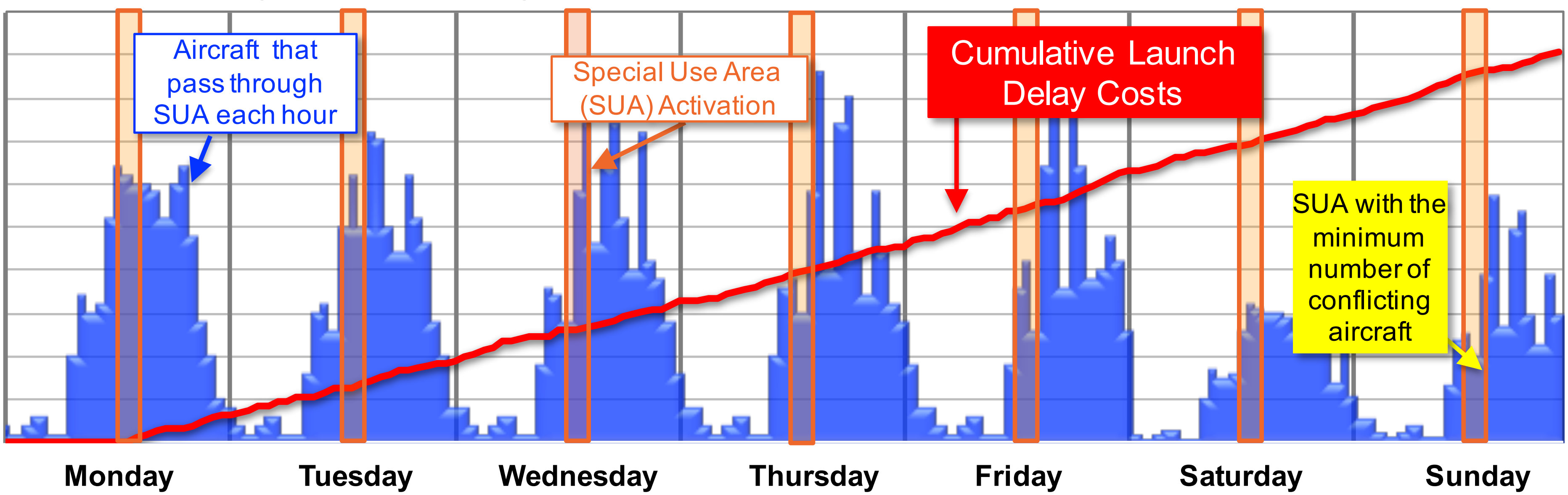
# Operational Approaches for Reducing Aircraft Reroute Costs

1. **SUA activation length and launch Window**
2. **SUA size and location**
3. **Launch schedule**

**Changing the Launch Window**

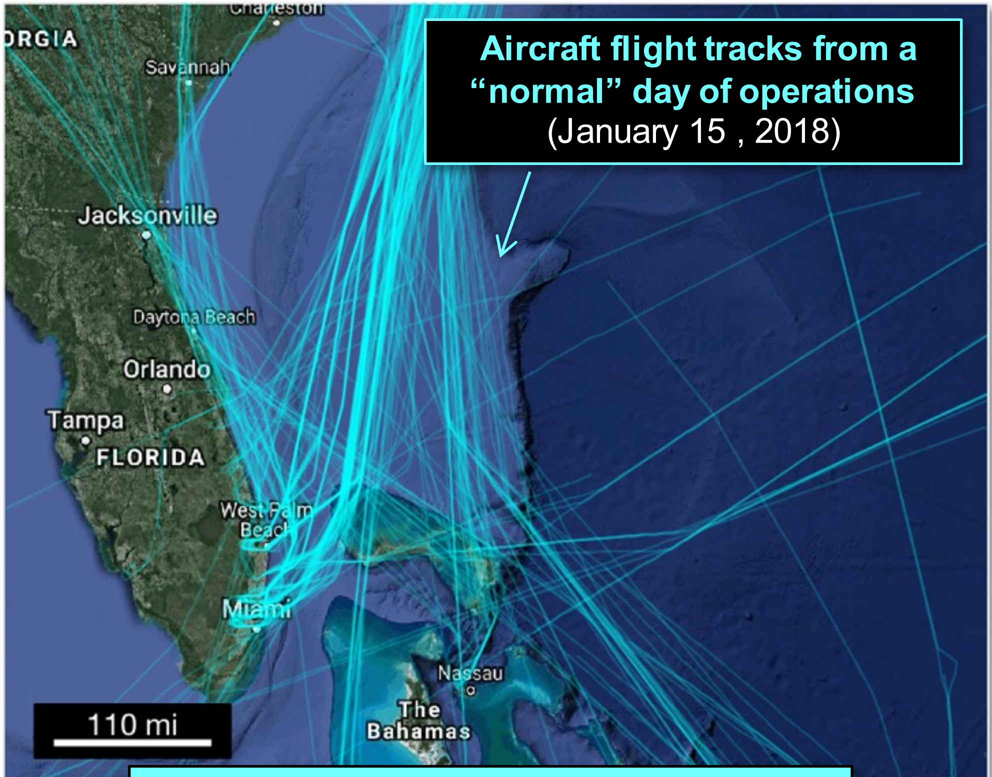


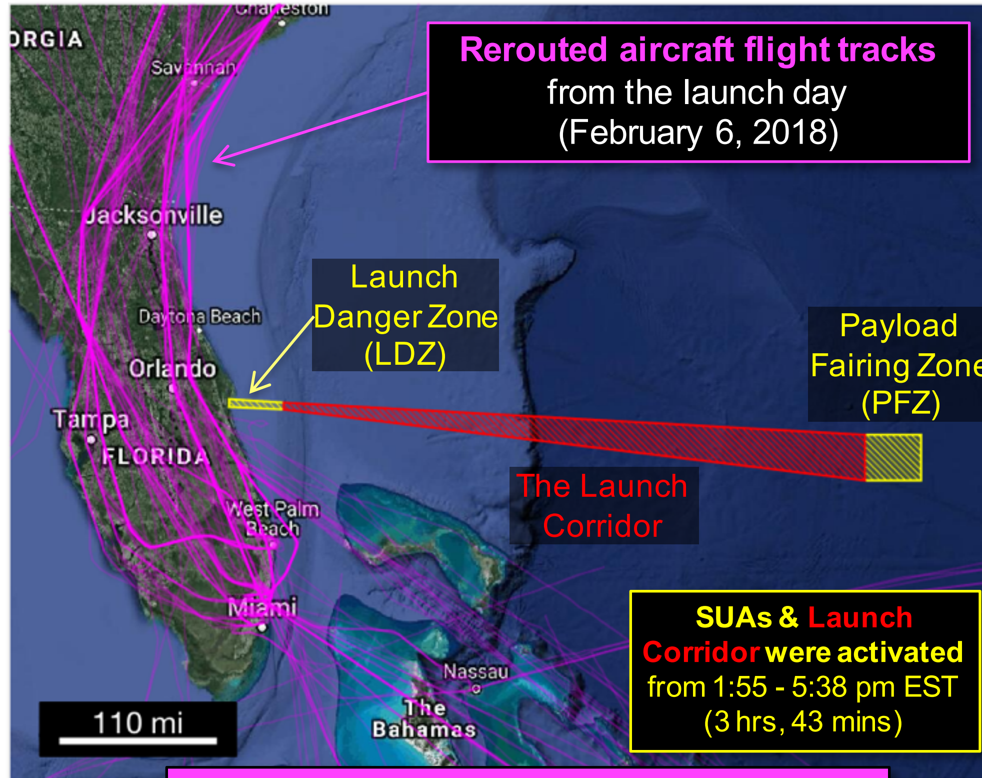

**A Notional 7-day Week with Daily Launch Opportunities**



# Equity and Cost Considerations for Space Launch Airspace Allocation

**Preliminary Aircraft <u>Rerouting Analysis</u> for the 2018 Falcon Heavy Launch**




**Cost of Delaying the Launch** to maintain "normal" air traffic operations

*-versus-*

**Cost of Rerouting Aircraft** for the space launch

- One way to discuss equity is to consider aircraft rerouting costs with launch delay costs
- Airline operating costs are known, however, there is little, to no cost information for launch operations and delays

→ Therefore, we need a commercial space operator cost model

# The Commercial Space Operator Cost Model

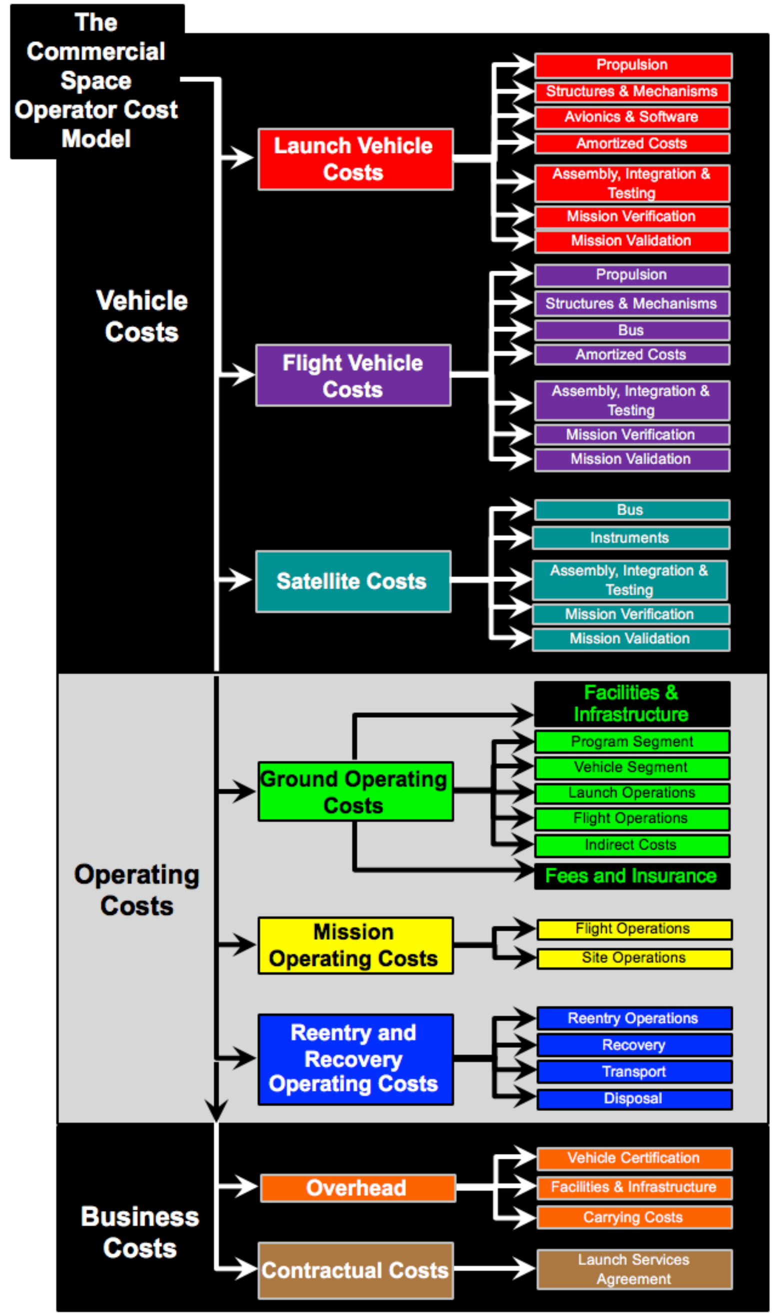
- The commercial space operator cost model can estimate space operator costs, and therein cost-equity

- The cost model can specifically estimate the cost of:
  1. new space vehicles and their operations; and
  2. potential launch delays and schedule slips.

- Existing space cost models have limited utility because:
  1. they are based on obsolete vehicles;
  2. use government or proprietary data; and
  3. do not quantify the cost of launch delays.

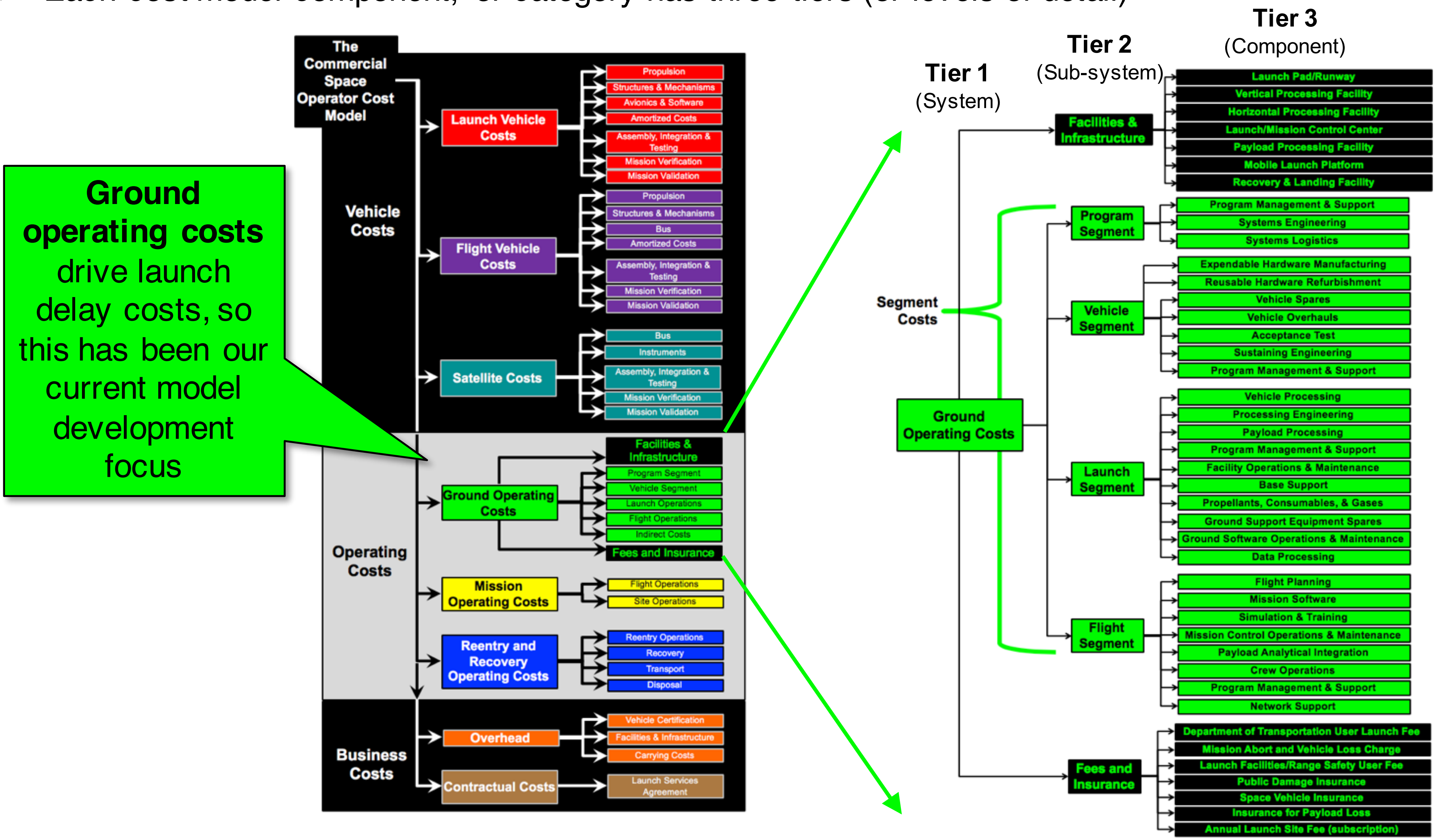
- Currently, there are two key results from the model:
  1. the absolute cost of a space mission; and
  2. the cost of potential a launch delay to a mission.

- The cost model is still under development



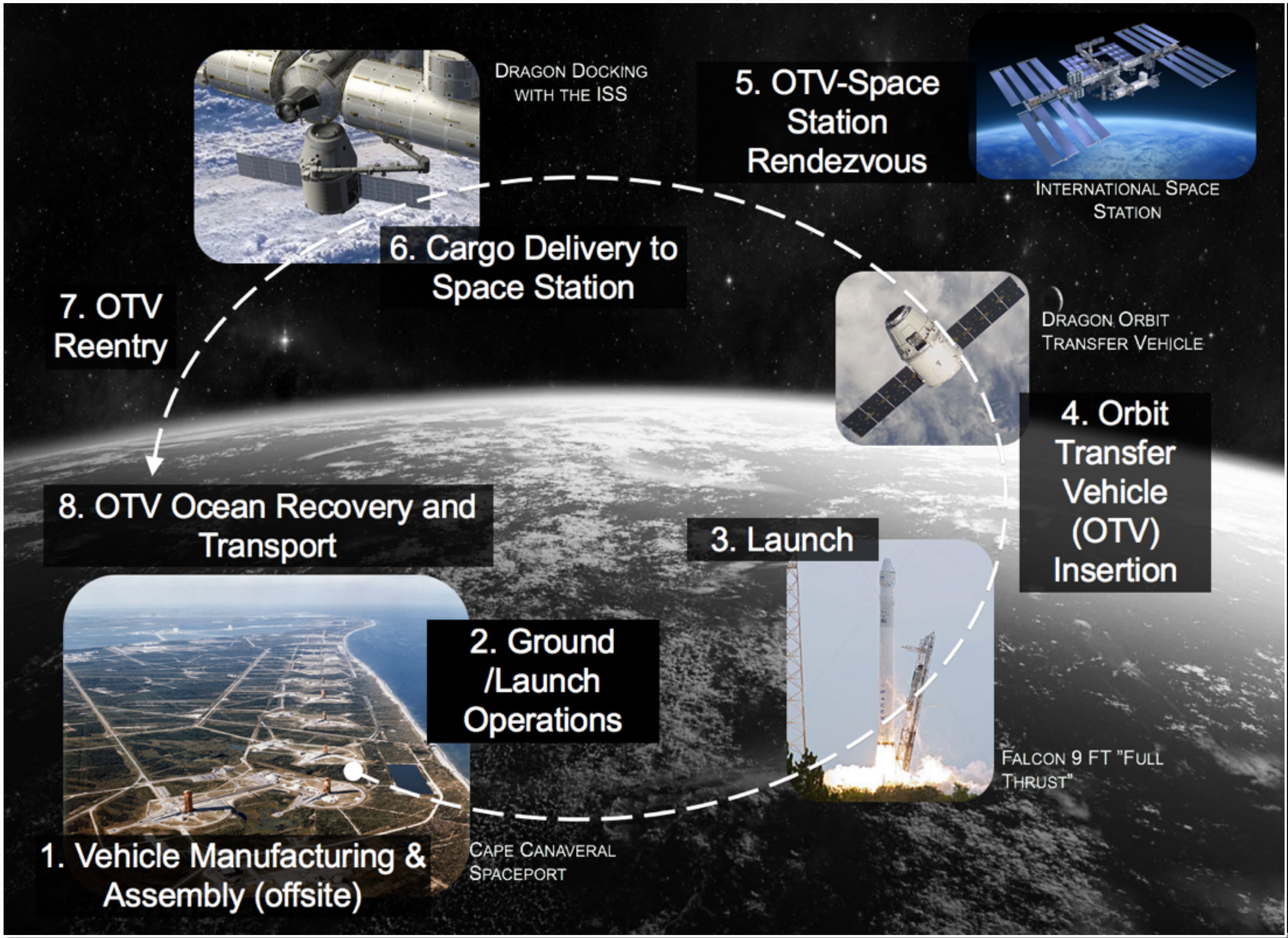
# Ground Operating Costs

- The cost model is parametric, or regression-based → $Cost = f(performance, mass, \ldots)$
- Each cost model component, or category has three tiers (or levels of detail)



# Initial Cost Model Validation

- A commercial SpaceX ISS cargo resupply mission was used as an initial validation



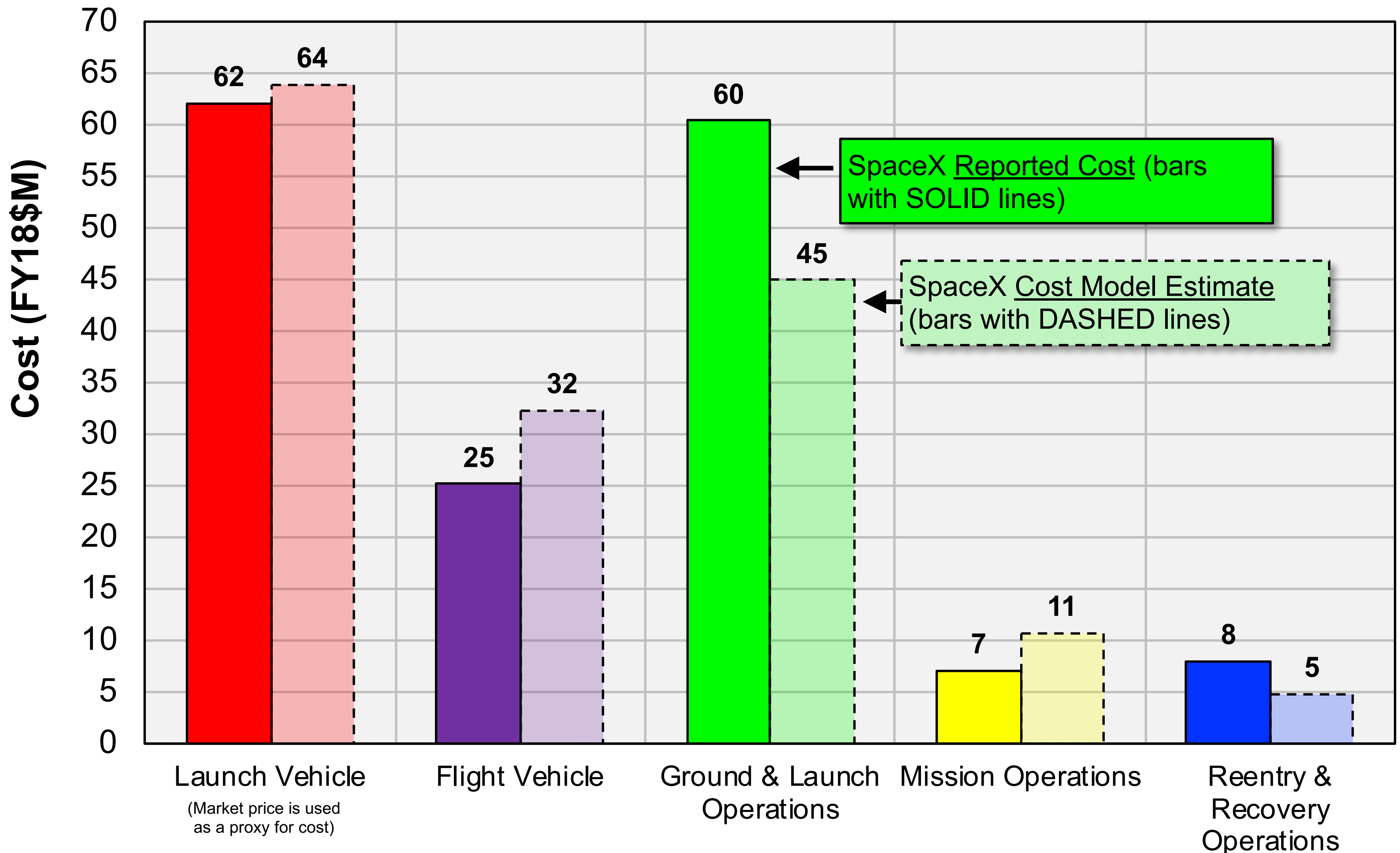

### Cost Model Inputs

- **Mission Type:** ISS Crew Cargo Resupply
- **Launch Site:** Cape Canaveral
- **Orbit:** 403 km altitude, 51.46° inclination
- **Launch Vehicle:** Falcon 9 FT "Full Thrust"
- **Flight Vehicle:** Dragon (4,200 kg dry mass)
- **Payload:** Pressurized cargo (3,500 kg)

- The commercial space operator cost model was run to estimate the total cost of this mission

# Preliminary Total Mission Cost Estimates

## Estimated versus Reported Costs for a SpaceX ISS Cargo Resupply Mission*




| | | |
|---|---|---|
| Reported Total Mission Cost: | 162.50 | FY18$M |
| Estimated Total Mission Cost: | 156.38 | FY18$M |
| Cost Difference (Estimate vs. Reported): | 6.12 | FY18$M |
| Cost Estimate Error: | 3.77 | % |

*Reported cost value sources: (1) Interviews with space launch experts; (2) open-source literature, articles; and (3) open-source launch vehicle and operations cost data. Refer to references for a detailed list of sources for all reported cost values.

# Potential Launch Delay Costs

➢ The ground operating cost model breakdown structure was used to locate the most likely sources of launch delay costs, but they remain hypotheses

## Potential Fixed Costs

**1. Propellant**
- Cost due to liquid fuel "boil-off" and vehicle de-tanking (draining) and tanking (refueling)

**2. Late payload delivery "penalty"**
- Payment to payload providers to partially compensate them for costs from a delay

**3. Launch Cancellation**
- Costs for "cancellation". A Launch Services Agreement would define a cancellation versus a delay.



## Potential Variable Costs

**1. Labor (overtime)**
- Work beyond the standard work shifts (*e.g.,* two, 8-hour shifts daily, excluding weekends)
- **The cost of overtime depends on:**
  1. Length of the delay/schedule shift
  2. Launch facilities
  3. Staffing at launch and mission ops
  4. Overtime rates
  5. Available launch windows
  6. Payload provider(s)
  7. Launch schedule & availability

➢ **Key Cost Model Result:** preliminary cost estimates for the change in space operator cost, due to off-nominal events such as launch delays and schedule slips

# Preliminary Launch Delay Cost Estimates

- Currently, the launch delay cost results are organized into a simple "lookup" table, where:
  - Table **ROWS** are the **Mission/Payload/Orbit**
  - Table **COLUMNS are Time** (except for fixed costs because these are independent of time)

**<u>Estimated Costs</u> of a <u>Launch Delay</u> to a SpaceX ISS Cargo Resupply Mission**

| FY2018$M | | | Variable Costs: Length of Delay after Launch Window | | | | | | Fixed Costs | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Confidence Level | Orbit Altitude (km) | Mission (Payload, Mass) | 15 minutes | 1 hour | 1 day | 10 days | 25 days | 50 days | Propellant | Late Payload Delivery "Penalty" | Cancellation |
| Low | 32,000+ | Interplanetary (Probes, 1000–4000 kg) | 0.8 | 1.0 | 1.3 | 3.6 | 16.7 | 41.7 | 1.1 | 0.4 | 58.3 |
| Low | 400 – 32,000 | Earth Orbit (Heavy Satellite, 12000–25000 kg) | 0.5 | 0.6 | 0.8 | 2.2 | 10.0 | 25.0 | 0.7 | 0.3 | 35.0 |
| Low | 400 – 32,000 | Earth Orbit (Medium Satellite, 4000–12000 kg) | 0.3 | 0.3 | 0.4 | 1.2 | 5.3 | 13.3 | 0.4 | 0.1 | 18.7 |
| Medium | 400 – 32,000 | Earth Orbit (Small Satellite, 12000–4000 kg) | 0.2 | 0.3 | 0.3 | 0.9 | 4.0 | 10.0 | 0.3 | 0.1 | 14.0 |
| Medium | 400 | ISS Cargo Resupply (Crew Supplies, ~3500 kg) | 0.1 | 0.1 | 0.2 | 0.5 | 2.3 | 5.8 | 0.2 | 0.1 | ~~8.2~~ *No cancellation fee* |

| LOW | MEDIUM | HIGH | VERY HIGH |
|---|---|---|---|
| Cost < $1M | $1M < Cost < $10M | $10M < Cost < $20M | $20M < Cost |

- Approximate cost of a 1-day/24-hour launch delay to a SpaceX cargo resupply mission is $0.4M

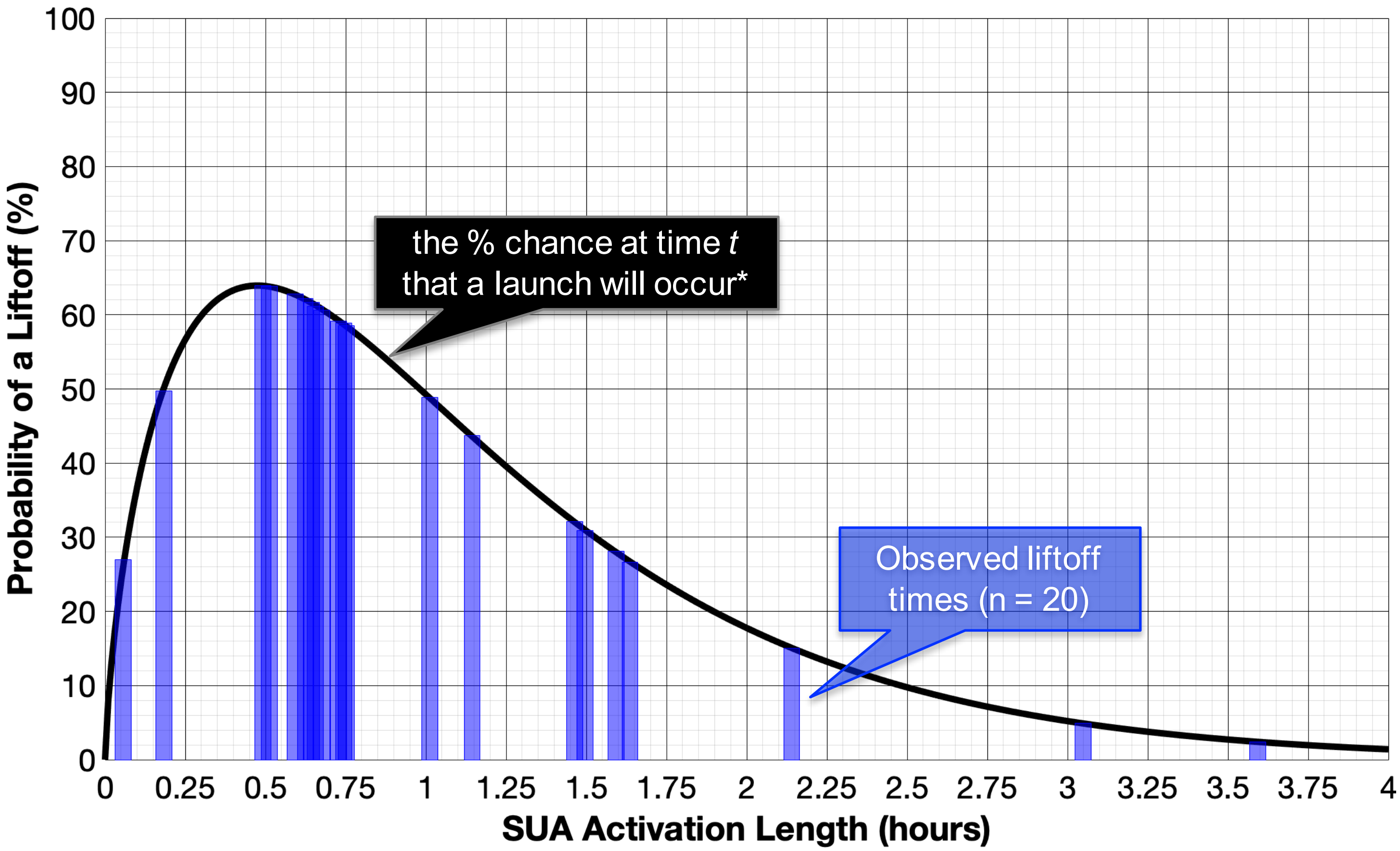
→ The results have not yet been validated and we have varying levels of confidence in the results, so they remain notional for time being

# Probability of Liftoff (%)

## for launches from Cape Canaveral

- We surveyed 20 past SUA activation periods and liftoff times for launches from Cape Canaveral
  - This limited dataset of SUA activation periods was the best available from the FAA NOTAM archive

- The result is a probability density function of the % chance of liftoff versus time into a "standard" 4-hour SUA activation for launches from Cape Canaveral

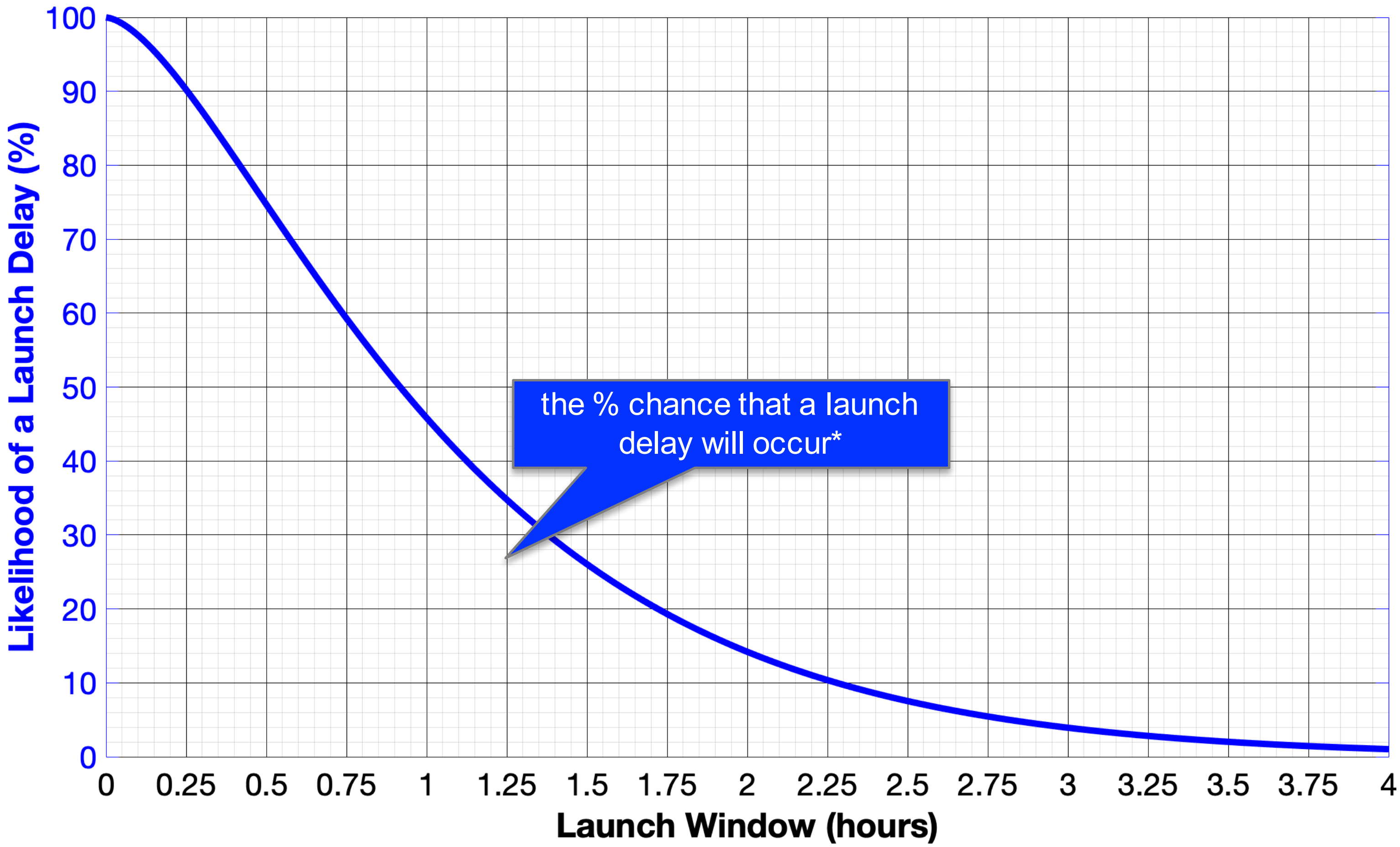



- Launch delays can arise from many factors, including:
  1. **Adverse weather conditions** (*e.g.,* high altitude wind shear and lightning)
  2. **Technical issues** – anomalies during countdown (*e.g.,* off-nominal system signal)

# Likelihood of a Launch Delay (%)

for launches from Cape Canaveral

- Cumulative probability density function of the % chance of a launch delay versus launch window length




- Launch delays can arise from many factors, including:
  1. **Adverse weather conditions** (*e.g.,* high altitude wind shear and lightning)
  2. **Technical issues** – anomalies during countdown (*e.g.,* off-nominal system signal)

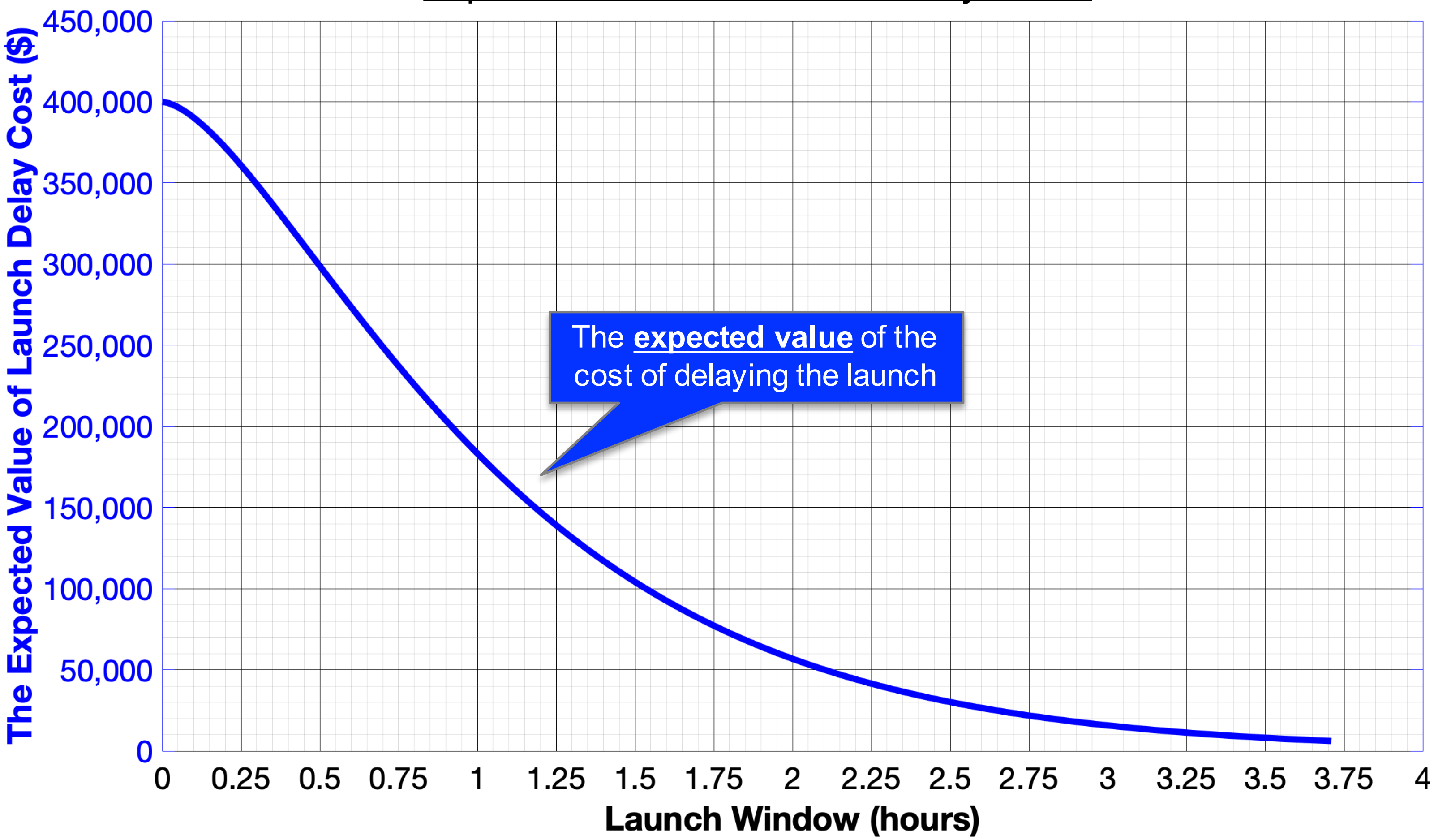
# The Expected Value of Launch Delay Cost ($)

## for ISS launches from Cape Canaveral

- To quantify the *expected value* launch delay costs, we multiply launch delay costs with the likelihood (probability) of launch delay pdf on the previous slide

$$\text{Expected Value of Launch Delay Cost} = E[DelayCost] = \sum_{i=1}^{n} DelayCost_i \cdot P(DelayCost_i)$$

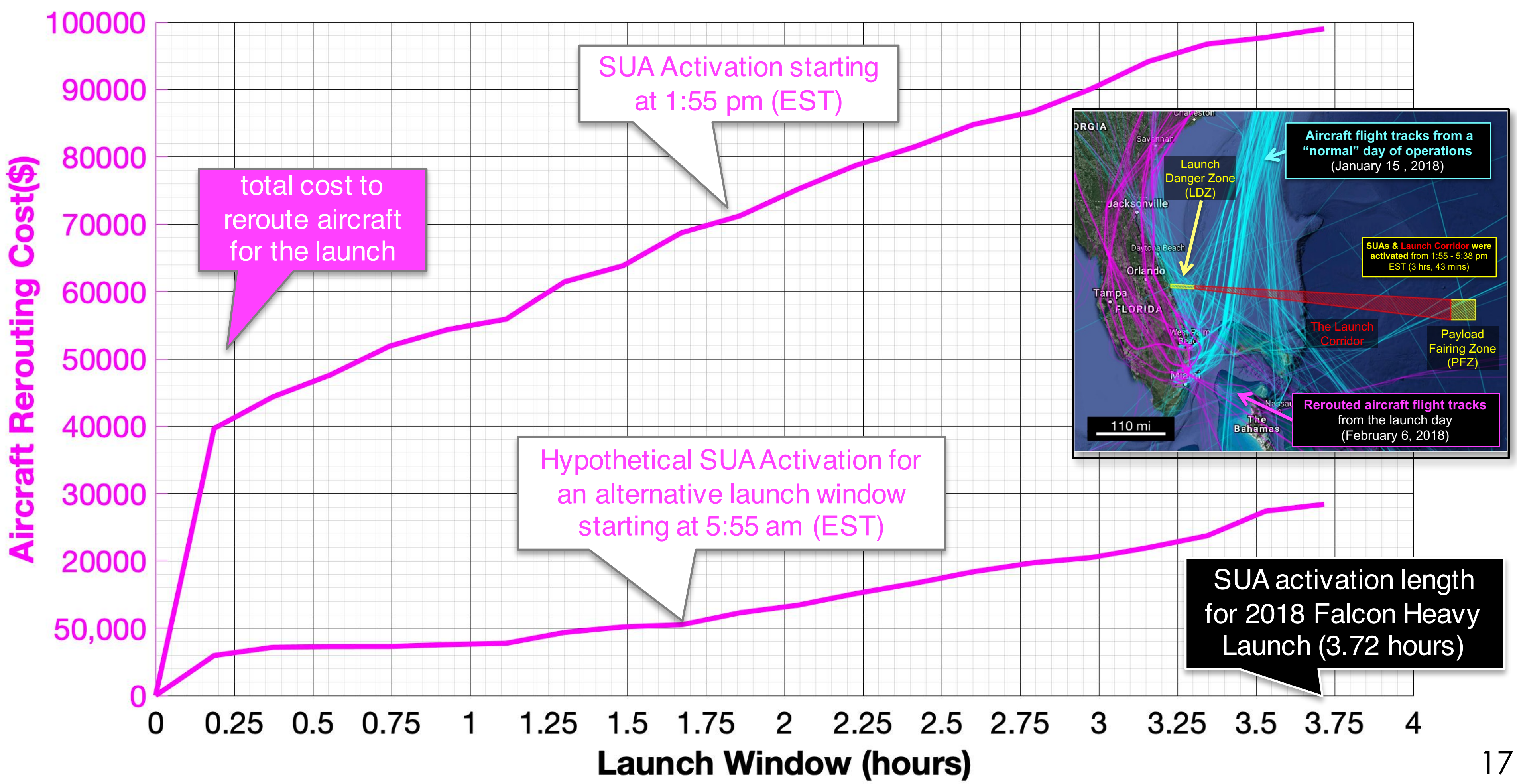
- The result is a distribution of expected value of launch delay costs versus launch window length



# Aircraft Rerouting Costs ($)

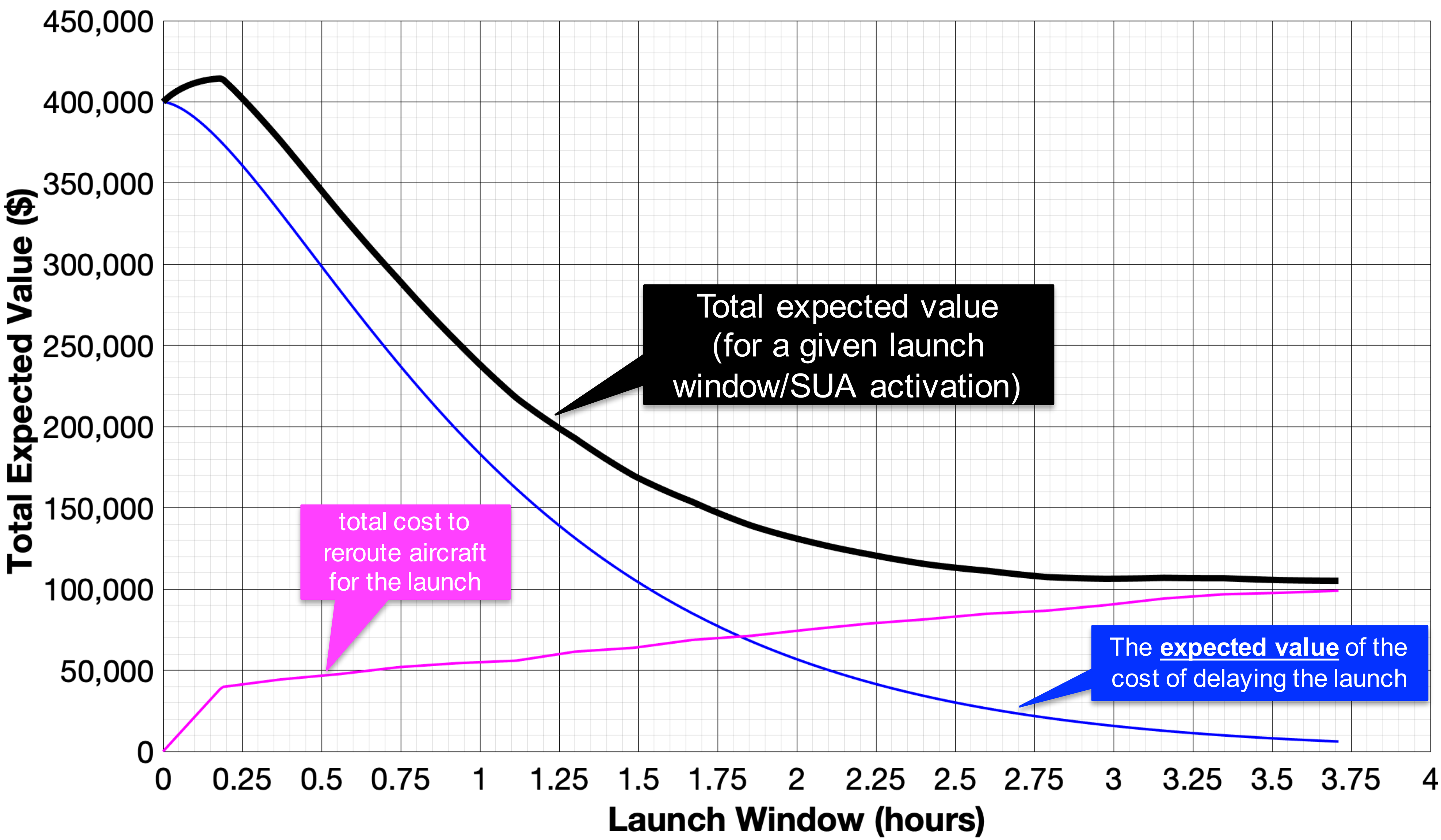
## for launches from Cape Canaveral

- Similar to launch delay costs, aircraft reroute costs depend on the SUA activation length
- However, aircraft reroute costs are deterministic because the reroutes can be planned in advance of the SUA activation for a space launch
- The result is the distribution <u>aircraft rerouting costs</u> versus launch window length



# Total Expected Value vs. Launch Window

for launches from Cape Canaveral



# References (1)

**Ongoing interviews, discussions, and presentations from subject matter experts at:**


1. FAA: Office of Performance & Analysis; Office of Commercial Space; Air Traffic Organization; ATO-International, Office of Investment, Planning, & Analysis; Technical Command Center; and Commercial Space Integration Team. (Oct. 2016 – present)
2. KT Engineering Corporation, Webb, R. (Oct. 2016 – present)
3. Princeton Synergetics Inc., Greenberg, J. (Aug. 2017 – present)
4. Victory Solutions Inc., Alford, B. (Feb. 2017 – present).
5. NASA Marshall (Cost Engineering Group), Prince, A. (Feb. 2017 – Apr. 2017).
6. United Launch Alliance (East Coast Launch Operations Group), Taliancich, A. G. (Feb. 2017 – Apr. 2017).
7. Aerospace staff and faculty at Massachusetts Institute of Technology, Crawley, E. F., and Widnall, S. (Feb. 2017)
8. SpaceX, Schenewerk, C. (November 2017).
9. Blue Origin, Mitchell, M. (November 2017).
10. Airlines for America, Cirillo, M. (Dec. 2017).


**Open-source literature, articles, and publicly available data, from:**

**Launch Providers**


11. SpaceX: http://www.spacex.com/about/capabilities
12. United Launch Alliance, Rocket Builder: https://www.rocketbuilder.com/
13. United Launch Alliance, "United Launch Alliance," Company Overview Available: http://www.ulalaunch.com/about-ula.aspx.
14. Orbital ATK, J., "Pegasus," Pegasus Available: https://www.orbitalatk.com/flight-systems/space-launch-vehicles/pegasus/.
15. Orbital ATK, http://www.northropgrumman.com/MediaResources/MediaKits/Space/Portfolio.aspx
16. Delta IV Launch Services User's Guide , June 2013 https://www.ulalaunch.com/docs/default-source/rockets/delta-iv-user's-guide.pdf.


**FAA**


17. Commercial Space and Launch Insurance: Current Market and Future Outlook, FAA Office of Commercial Space Transportation. https://www.faa.gov/about/office_org/headquarters_offices/ast/media/q42002.pdf
18. FAA Office of Commercial Space Transportation, "Launch or Reentry Vehicles" Available: https://www.faa.gov/about/office_org/headquarters_offices/ast/licenses_permits/launch_reentry/.
19. FAA Office of Commercial Space Transportation, The Economic Impact of Commercial Space Transportation on the U.S. Economy in 2009, FAA Office of Commercial Space Transportation, 2010. https://www.faa.gov/news/updates/media/Economic%20Impact%20Study%20September%202010_20101026_PS.pdf
20. FAA Office of Commercial Space Transportation, The Annual Compendium of Commercial Space Transportation: 2016, FAA Office of Commercial Space Transportation, 2016. https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2016_Compendium.pdf
21. Federal Aviation Administration, "Year in Review," Reports & Studies Available: https://www.faa.gov/about/office_org/headquarters_offices/ast/reports_studies/year_review/.
22. FAA Office of Commercial Space Transportation, "Commercial Space Transportation Forecasts," Reports & Studies Available: https://www.faa.gov/about/office_org/headquarters_offices/ast/reports_studies/forecasts/.

# References (2)

**Open-source literature, articles, and publicly available data, from:**


**News Articles & Online Publications**

23. NBC News: Boyle, Alan (18 August 2006). "SpaceX, Rocketplane win spaceship contest". MSNBC. New York. Archived from the original on 18 December 2011. Retrieved 18 December 2011. < http://www.nbcnews.com/id/14411983/ns/technology_and_science-space/t/spacex-rocketplane-win-spaceship-contest/#.WuCZpsiQwWo>
24. Business Insider, http://www.businessinsider.com/spacex-rocket-cargo-price-by-weight-2016-6
25. Spaceflight Now, https://spaceflightnow.com/antares/cots1/130904frr
26. Small World Communications, Pietrobon, S., "United States Commercial ELV Launch Manifest (1 Mar 2017)" Available: http://www.sworld.com.au/steven/space/uscom-man.txt
27. Space News, Foust, J., "SpaceNews," Bolden Praises Continued Cooperation with Russia on ISS Available: http://spacenews.com/bolden-praises-continued-cooperation-with-russia-on-iss/.
28. Woolley, J., and Peters, G., "Statement on Signing the Commercial Space Launch Act - October 30, 1984," The American Presidency Project Available: http://www.presidency.ucsb.edu/ws/?pid=39335.
29. Space News, SpaceX President Gwynne Shotwell in 2016 on the cost of ISS Cargo Resupply Missions <http://spacenews.com/spacex-wins-5-new-space-station-cargo-missions-in-nasa-contract-estimated-at-700-million/>
30. Space News, Foust, J., "Bezos Investment in Blue Origin Exceeds $500 Million," SpaceNews Available: http://spacenews.com/41299bezos-investment-in-blue-origin-exceeds-500-million/.
31. Space News, Foust, J., "NASA Delays Award of Commercial Cargo Follow-on Contracts," SpaceNews Available: http://spacenews.com/nasa-delays-award-of-commercial-cargo-follow-on-contracts/
32. LA Times, Stewart, R. W., "Congress Boosts Private Rocket Launching Services" Available: http://articles.latimes.com/1990-10-30/business/fi-3554_1_launch-services.
33. Planetary Society, http://www.planetary.org/blogs/jason-davis/2017/201705011-data-orbital-spacex.html
34. Space News, Foust, J., "NASA Delays Award of Commercial Cargo Follow-on Contracts," SpaceNews Available: http://spacenews.com/nasa-delays-award-of-commercial-cargo-follow-on-contracts/.
35. Planet Labs, "Planet Labs," Products Available: https://www.planet.com/
36. Space, Howell, E., "SpaceShipTwo: On a Flight Path to Space Tourism," Space.com Available: http://www.space.com/19021-spaceshiptwo.html.

**Books/Manuals**

37. Larson, W. J., and Wertz, J. R., Space Mission Analysis and Design (SMAD), New York, New York: Microcosm Press, 1999.
38. Kolle, D., Handbook of Cost Engineering for Space Transportation Systems, Ottobrun, Germany: TransCostSystems, 2010.

**Manuals/Databases**

39. Webb, R., Conceptual Operations Manpower Estimating Tool and Operations Cost Model (COMET/OCM), Version 1.1, Rancho Dominguez, CA: KT Engineering, 2004.
40. Wade, M., "Encyclopedia Astronautica," Encyclopedia Astronautica Available: http://www.astronautix.com/index.html.
41. Gunter's Space Page: http://space.skyrocket.de/doc_sdat/dragon.htm.
42. Kyle, E., "Annual Space Reports," Space Launch Report Available: http://www.spacelaunchreport.com/.
43. McDowell, J., "Jonathan's Space Home Page," JSR Launch Vehicle Database, 2016 Dec 30 Edition Available: http://www.planet4589.org/space/.

# References (3)

**Open-source literature, articles, and publicly available data, from:**


**NASA**

44. "Commercial Orbital Transportation Services (COTS)," Commercial Space Transportation Available: https://www.nasa.gov/commercial-orbital-transportation-services-cots.
45. NASA, "NASA Releases COTS Final Report" Available: https://www.nasa.gov/content/nasa-releases-cots-final-report.
46. NASA, "Kennedy Space Center," Space Shuttle and International Space Station Available: https://www.nasa.gov/centers/kennedy/about/information/shuttle_faq.html#1
47. NASA, "Project Cost Estimating Capability (PCEC)," 2015-2016 Software Catalog Available: https://software.nasa.gov/featuredsoftware/pcec.
48. NASA, NASA Cost Estimating Handbook, Version 4.0, Washington, D.C.: National Aeronautics and Space Administration, 2015. https://www.nasa.gov/offices/ocfo/nasa-cost-estimating-handbook-ceh
49. NASA, "Commercial Space Act of 1998, Title II - P.L. 105-303" Available: https://www.nasa.gov/offices/ogc/commercial/CommercialSpaceActof1998.html.
50. NASA Office of Inspector General & Audits, "NASA OIG Audit of Commercial Resupply Services to the International Space Station", published April 26 2018, available: https://oig.nasa.gov/docs/IG-14-031.pdf.
51. NASA Awards Launch Services Contract for Maven Mission". NASA Mars Exploration Program. 21 October 2010. Retrieved 7 May 2016. http://www.spaceref.com/news/viewpr.html?pid=31905.

**Government**

52. Department of Defense, Defense Procurement and Acquisition Policy, "Contract Type Table," Defense Contingency Contracting Officer's Representative Handbook and Additional Contracting Officer's Representative Guidance Available: https://www.acq.osd.mil/dpap/index.html.

**Open-source Space Cost Models**

53. Unmanned Space Vehicle Cost Model (parametric)
54. Small Satellite Cost Model, The Aerospace Corporation (parametric)
55. Project Cost Estimating Capability (PCEC), NASA (parametric)
56. Missions Operations Cost Estimation Tool, The Aerospace Corporation (parametric)
57. TRANSCOST Model, Koelle, D. (parametric, analogy)