Detailed Analysis of EM-1 Cubesat Deployments & 4-MSPA Implications

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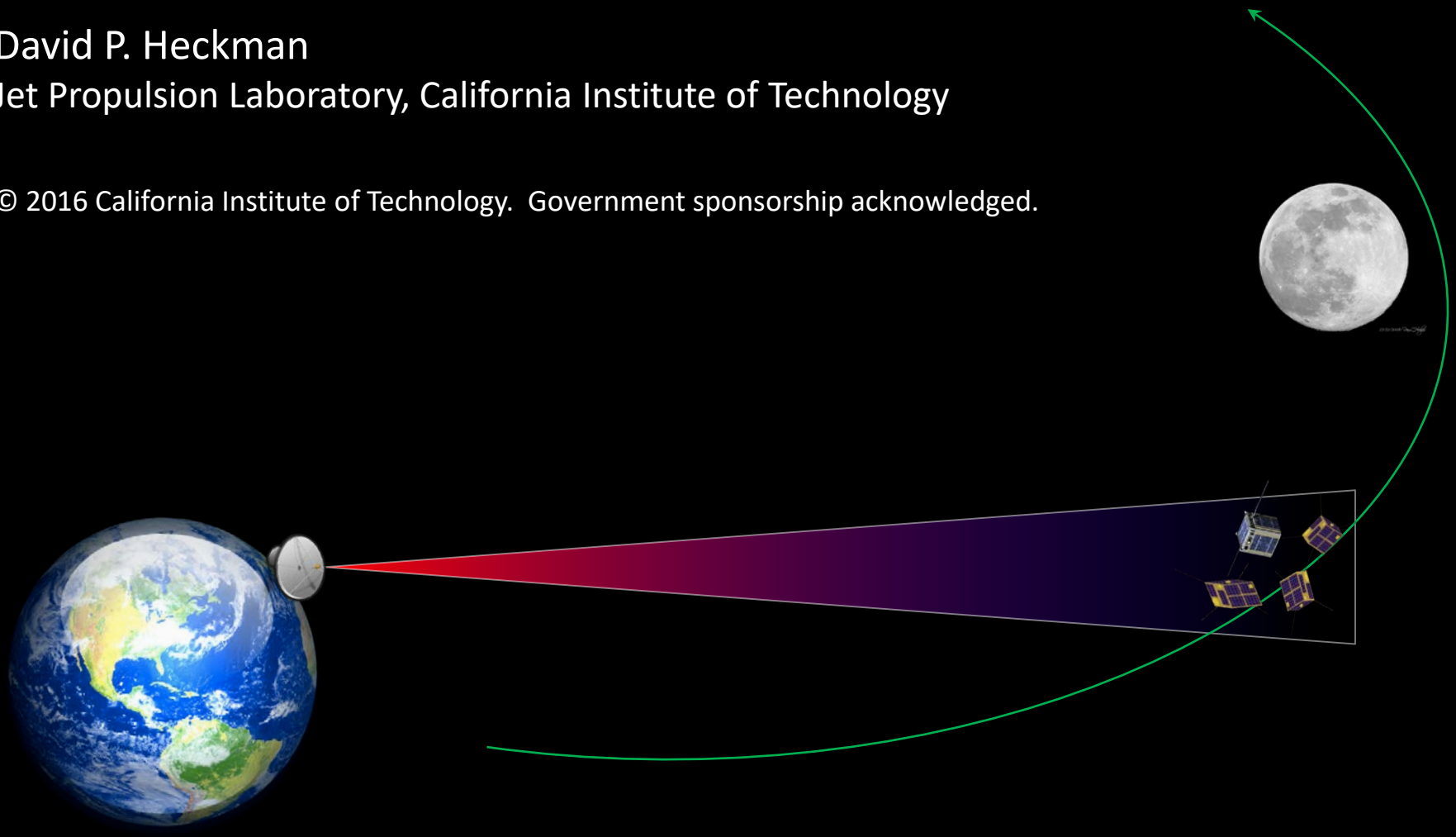
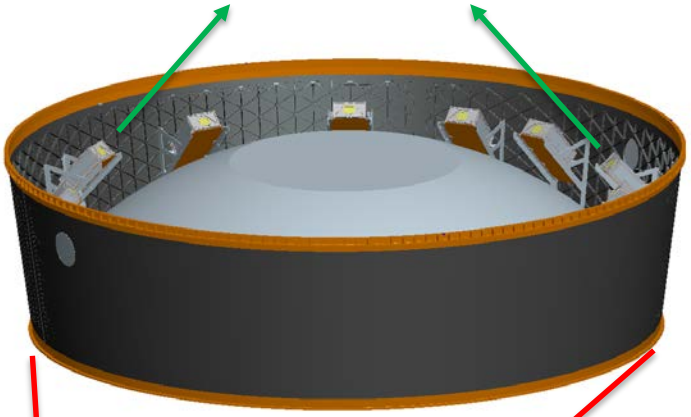
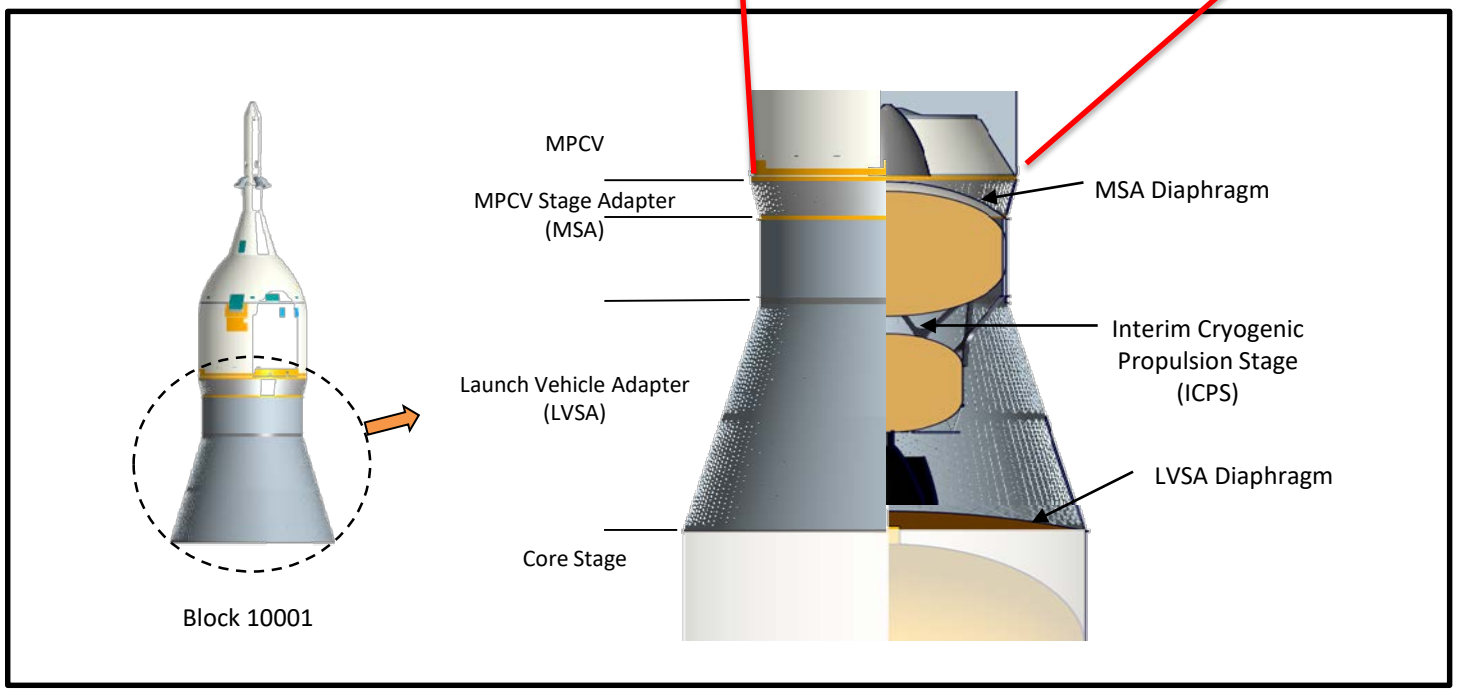


SLS & ICPS Overview

After separation from MPCV, the ICPS will lose power. A sequencer will then release cubesats using spring-loaded mounts in the adapter ring.

Positioning of the deployers inside the fairing and the angle of them with respect to the ICPS axis are known (proposed) and are study inputs.





Diagrams supplied by **Scott Spearing**, Marshall Space Flight Center: *SLS Secondary Payload Monthly User Forum*

ICPS & Deployment General Info

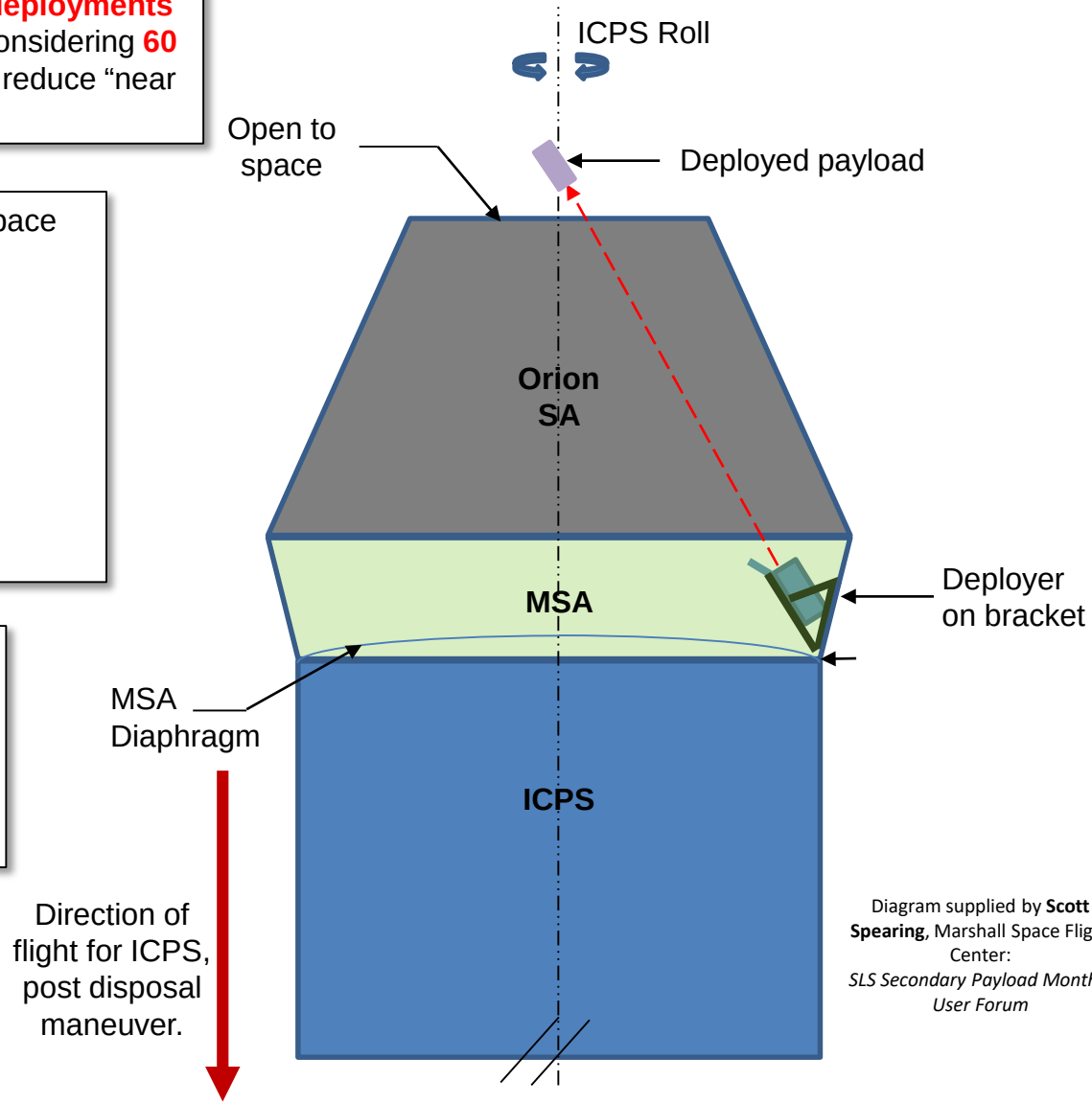
There is a **5 sec. minimum between payload deployments** to avoid payload to payload collisions. We are considering **60 sec. delays between payload deployments** to reduce "near field" re-contact of payloads.

CubeSat "Bus Stops" are currently based on space environments & locations to the moon.

Bus Stop #	Event/Location
1	First opportunity to deploy
2	½ through Van Allen belt
3	1+ hr. past Van Allen belt
4	½ to moon
5	At moon
6	~6 hr. past moon

Spring deployment velocity for max. weight payload (14 kg) is **1.2 m/s**. Lighter payloads will have a slightly higher velocity. Any spring failures will cause a decrease in velocity (see spring chart. Dispenser springs are "constant force" springs.

ICPS will be in a **1 rpm roll about its long axis**. Direction of roll (clockwise or counter clockwise) has **not** been determined by ULA at this time.



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Deployment "Bus Stops"

The 3 bus stops highlighted in red were evaluated in this study.

EM-1 Cubesat Deployment Events/Definition					
CubeSat "Bus Stops"	Sequence Time D/H/M/S	Mission Time D/H/M/S	Distance from Earth miles	Temp. Range °F	Comments:
System Initiation	00/00/00/08	00/04/42/28	16,600	-30° to 90°	
Reduced Radiation Risk	00/03/30/00	00/08/12/20	24,500?	-30° to 90°	Assumes ~75% rad. Drop
Clear Van Allen Belt	00/06/45/00	00/11/27/20	32,000?	-30° to 90°	Assumes no solar issues
At The Moon	04/22/36/05	05/03/18/22	238,900	-30° to 90°	Exterior temp. may be higher at moon (~30° to 50° higher) due to reflected light.
End of the Line	09/23/56/40	10/04/38/57	450,000?	-30° to 90°	Includes benefit of lunar gravity assist to ICPS & contents.

Assumptions:	
1	5 day trip to the moon is assumed.
2	1 rpm roll with the ICPS flying tail first.
3	ICPS will stay stable for >10 days without wobbling & tumbling.
4	Assumes a ~ 2 hour time from MPCV separation from ICPS to deployment start.
5	Payloads can be deployed between "bus stops".
6	10 paylaods or less can be deployed within 1 minute of a specific "bus stop".
7	

Study Outline

Earlier efforts by Bruce MacNeal and David Heckman provided some guidance using the assumption of **gravity-free** space and "simple" deployment rules.

Cubesats released on the EM-1 mission can reach the Moon while remaining within a single X-band 34m beam provided one of the following:

- *They are released in the **same direction** (same clock angle, same release angle)**
- *They are released with arbitrary (un-controlled) clock angles with release angles below the **critical limit*** $\sin\alpha < \frac{v_r}{2v_s} \tan\theta$

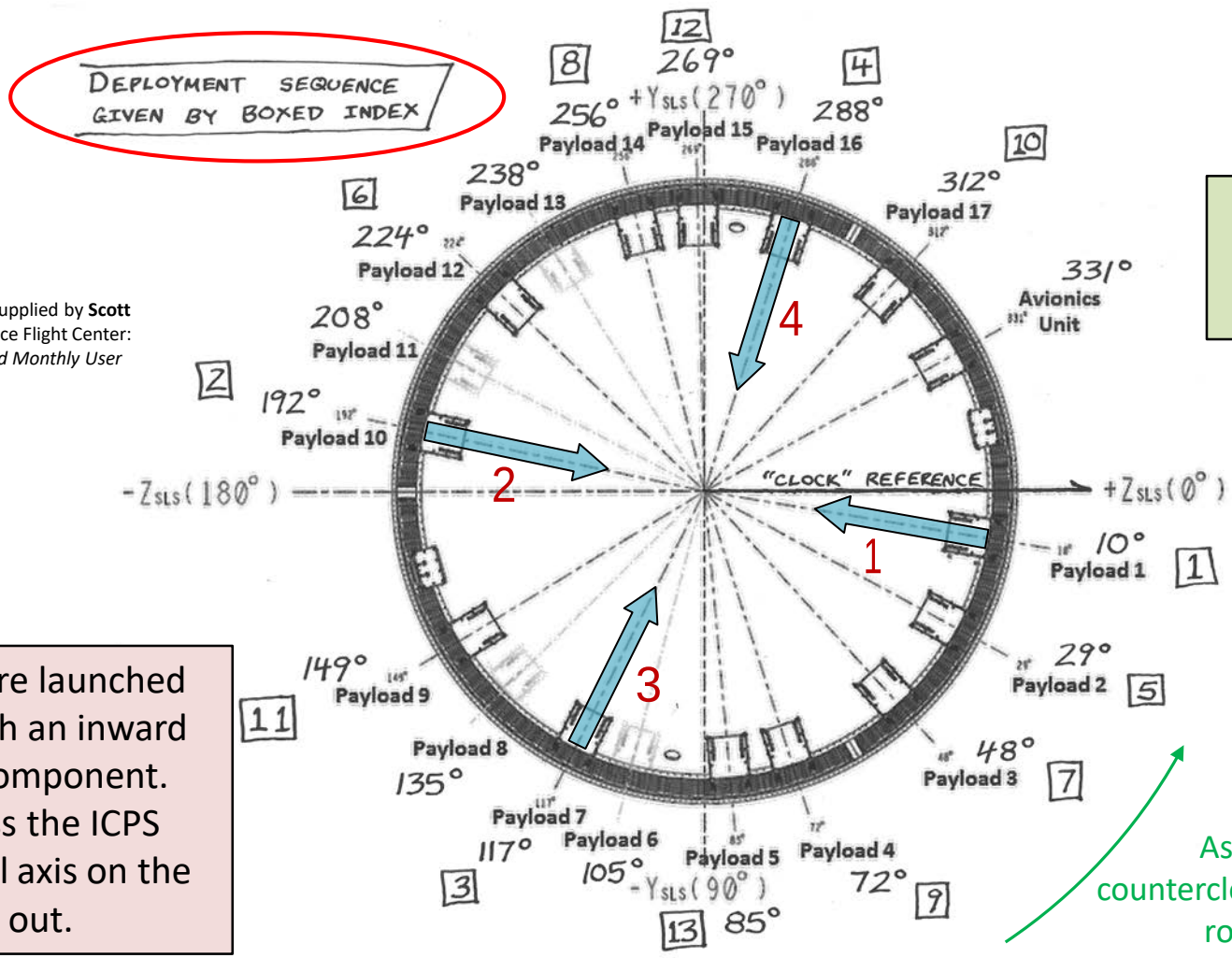
** Same-direction releases will require good knowledge of the "BBQ" roll rate. The exact direction is not very important, but having the <u>same</u> direction is.*

Many more pieces of information are now known (proposed.) This study will…

- Use four-body motion modeling throughout, not unaccelerated or "Kepler" motion
- Use the ICPS initial state vector & epoch given in **ROSES H-TIDeS14** document
- Focus on 3 of the 5 proposed bus stops and a few different temporal spacings
- Use the currently proposed cubesat deployment geometry
- Sample a range of cubesat deployment speeds and all ICPS "clock" angles
- Use a 4-MSPA "cluster width metric" to judge feasibility for groups of 4 cubesats

Payloads & Release Sequence

Top view of the ICPS, looking down into the cubesat payload area:



Payload ring diagram supplied by **Scott Spearing**, Marshall Space Flight Center: *SLS Secondary Payload Monthly User Forum*

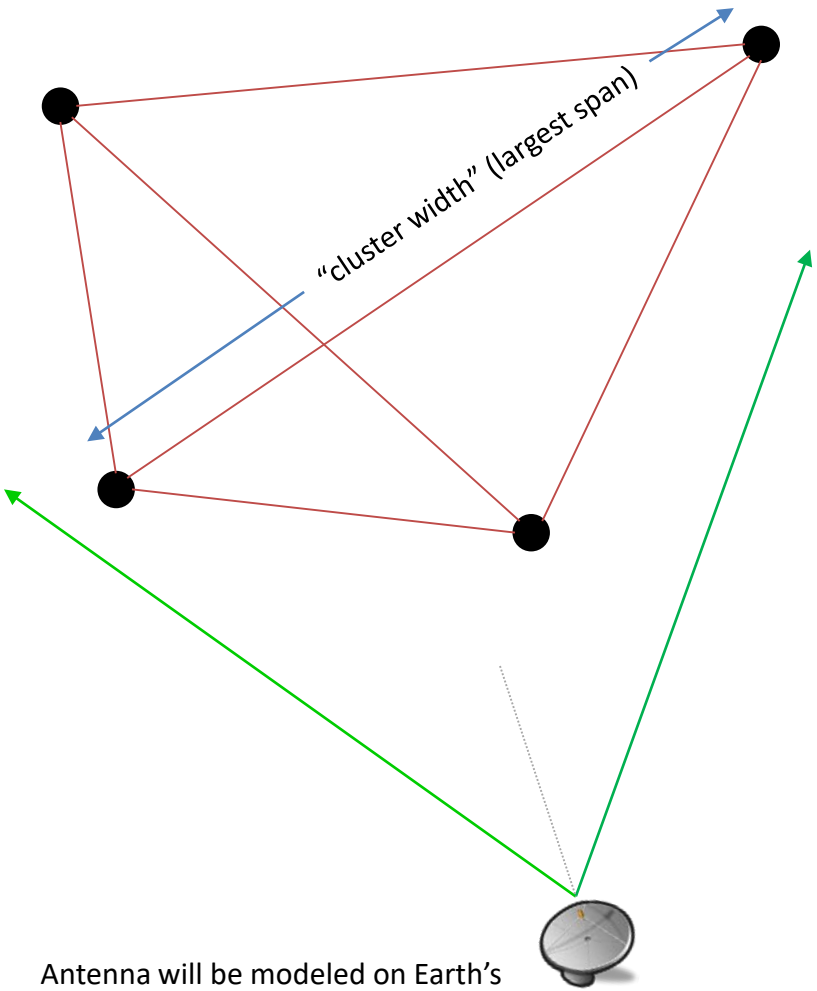
This "clock" reference is used in these studies.

Cubesats are launched radially with an inward velocity component. They cross the ICPS longitudinal axis on the way out.

Assuming a counterclockwise (1 RPM) roll of ICPS

A Definition of 4-MSPA Feasibility

4 cubesats: 6 different pairs to consider



Antenna will be modeled on Earth's surface and always in-view of ICPS.

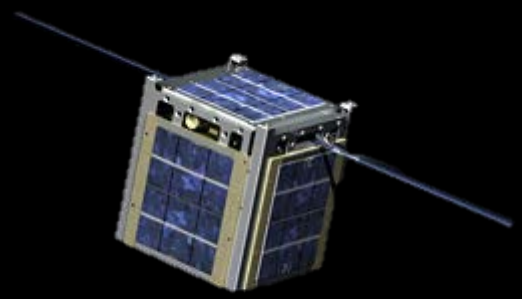
<u>4-MSPA geometric criterion</u>

The cubesat cluster satisfies general 4-MSPA feasibility if the "cluster width" (**largest** span seen at the antenna between **any pair)** is **smaller** than **half** of the beamwidth of the antenna.

Operations: With 4-MSPA feasibility, if an antenna can point at **any** single cubesat, then **all 4** cubesats are guaranteed to be in the beam. Assume in this study the beam width is **.066 degrees**.

This criterion is conservative. If a <u>particular</u> one was the tracked host, each of the other 3 just need to be within half a beamwidth of that host.

Trajectory & Motion Modeling



Four-body trajectory calculations for ICPS & all cubesats:
Gravity from the Earth, Moon & Sun

The antenna position is modeled as the ground track of the ICPS on Earth's surface (no site visibility effects.)

Sampled trade space:

- A few release start times ("bus stops")
- Release interval between cubesats (10, 30, 60 seconds)
- Clock angle of ICPS reference axis at release start
- Speed of cubesat launch from ICPS (1.2 m/s to 1.6 m/s)
- .066-degree beamwidth (X band, 34-meter antenna)

Typical ICPS & Cubesat Motions

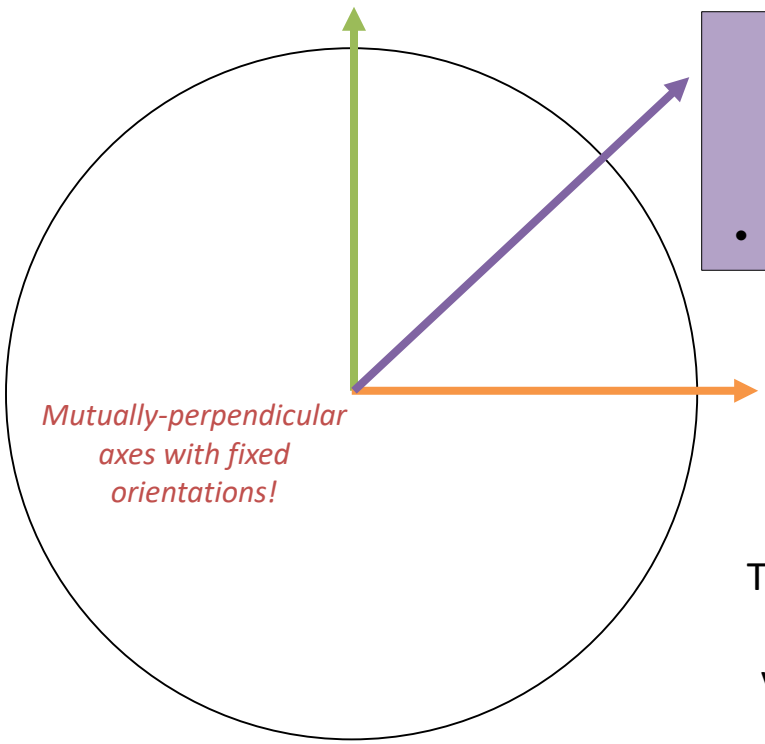
Plot Coordinate System

Plots of 4-MSPA performance are annular domains over cubesat speed and ICPS clocking. They have an implied coordinate system referenced to **Earth's polar axis** and the **ICPS initial velocity**.

Image plane *Y* axis

- perpendicular to the ICPS longitudinal axis
- perpendicular to the image plane *X*
- intuitively "up" to the ICPS

Note: The image plane *Y* axis and Earth's polar axis are not the same, but they and the ICPS longitudinal axis are all in the **same plane**.



ICPS longitudinal axis

- determined by initial ICPS velocity
- always "into" the visual plane
- ICPS orientation assumed stable in space
- assuming ICPS rolls **counterclockwise** about this axis

Image plane *X* axis

- perpendicular to ICPS longitudinal axis
- perpendicular to Earth's polar axis
- intuitively "right" to the ICPS

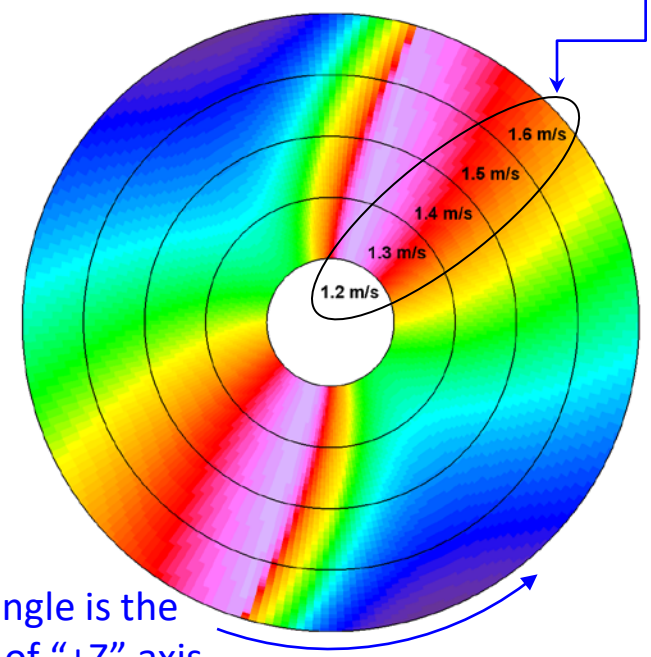
The plot image plane is perpendicular to the ICPS longitudinal axis, but is **not** always perpendicular to the instantaneous velocity vector of the ICPS. It is exactly perpendicular to the ICPS velocity vector only initially.

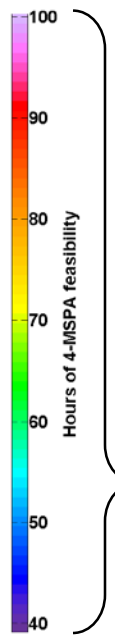
Interpreting Plotted Results

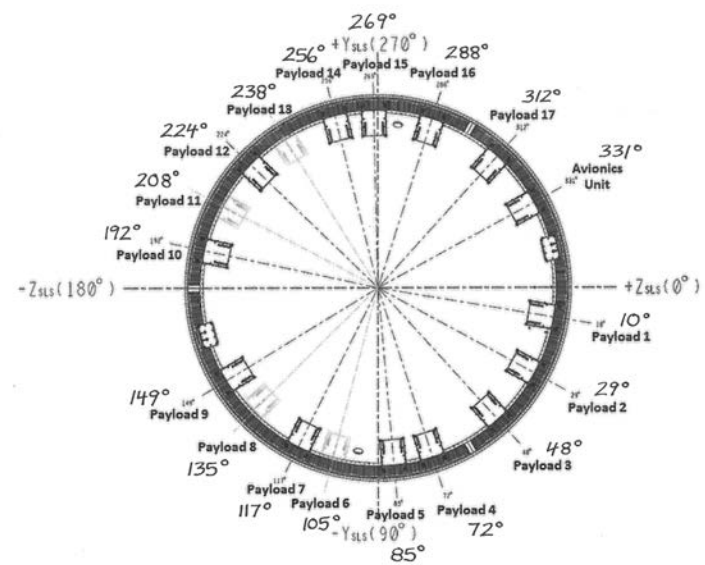
Plots of 4-MSPA performance are 3-dimensional, using color for one dimension.

- MSPA performance is given as **hours of feasibility** (for the cluster width metric), coded by color
- Cubesat release speed is referenced to the radial distance
- A given speed applies to **all 4** cubesats launched at the event/waypoint
- The "clock" angle is the angle of the ICPS ($+Z_{SLS}$) reference vector **at first unit release**

Cubesat speeds referenced to plot radius







The colorbar gives the numerical scale of the performance: **hours of 4-MSPA**

Most plots reference 7-day analysis periods.

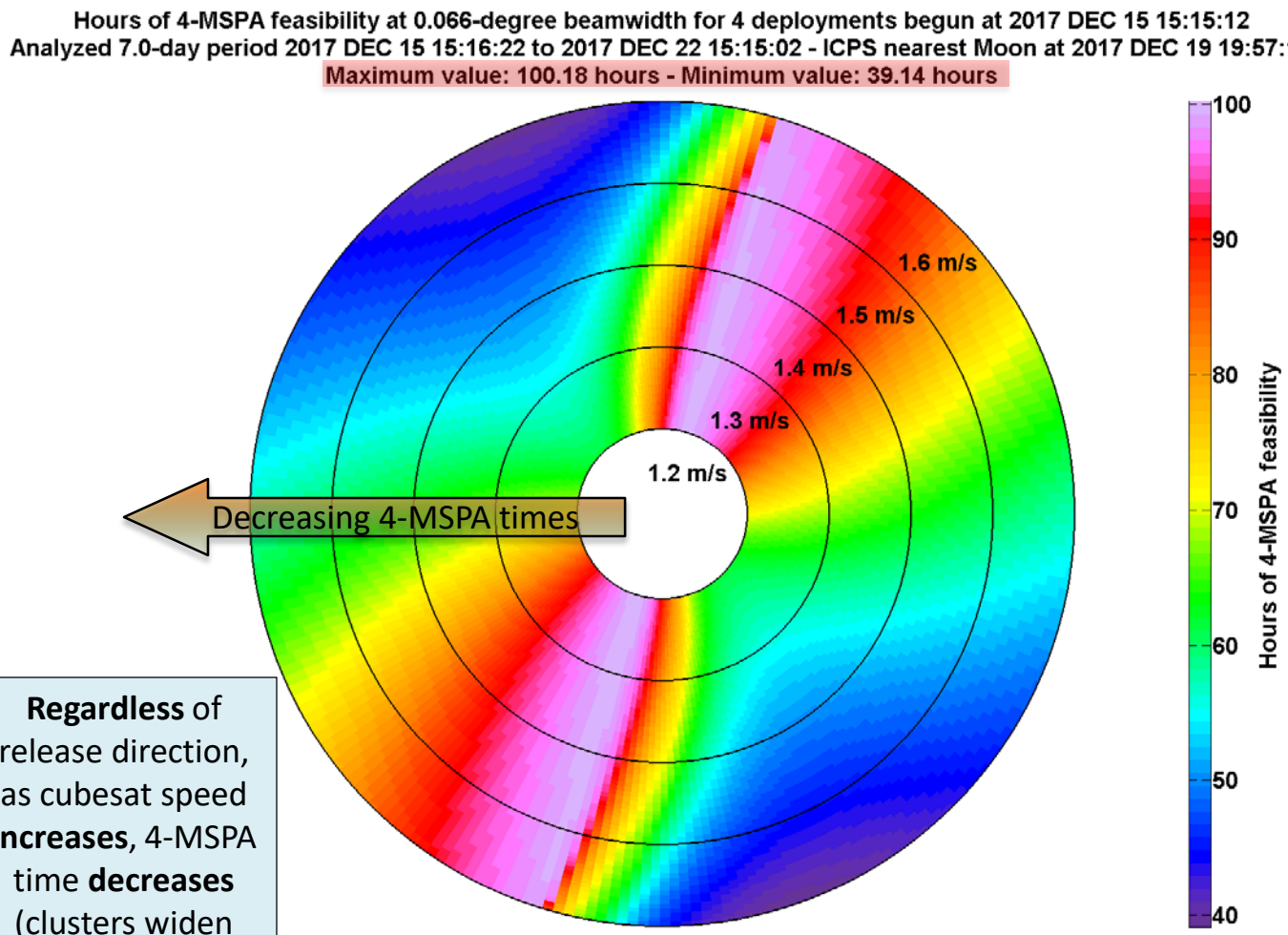
* The full color span is always used in each plot, but the numerical scale **varies**.

Clock angle is the clocking of "+Z" axis when releases **began**.

Releases at Stop #1, 10-second spacing

The first bus stop could allow for **days** of 4-MSPA feasibility in most cases.

Cubesats numbered 1 through 4 were deployed here.



There are about 100 hours from this release (2017 DEC 15 15:15:12) to the closest lunar approach (2017 DEC 19 19:57:16.)

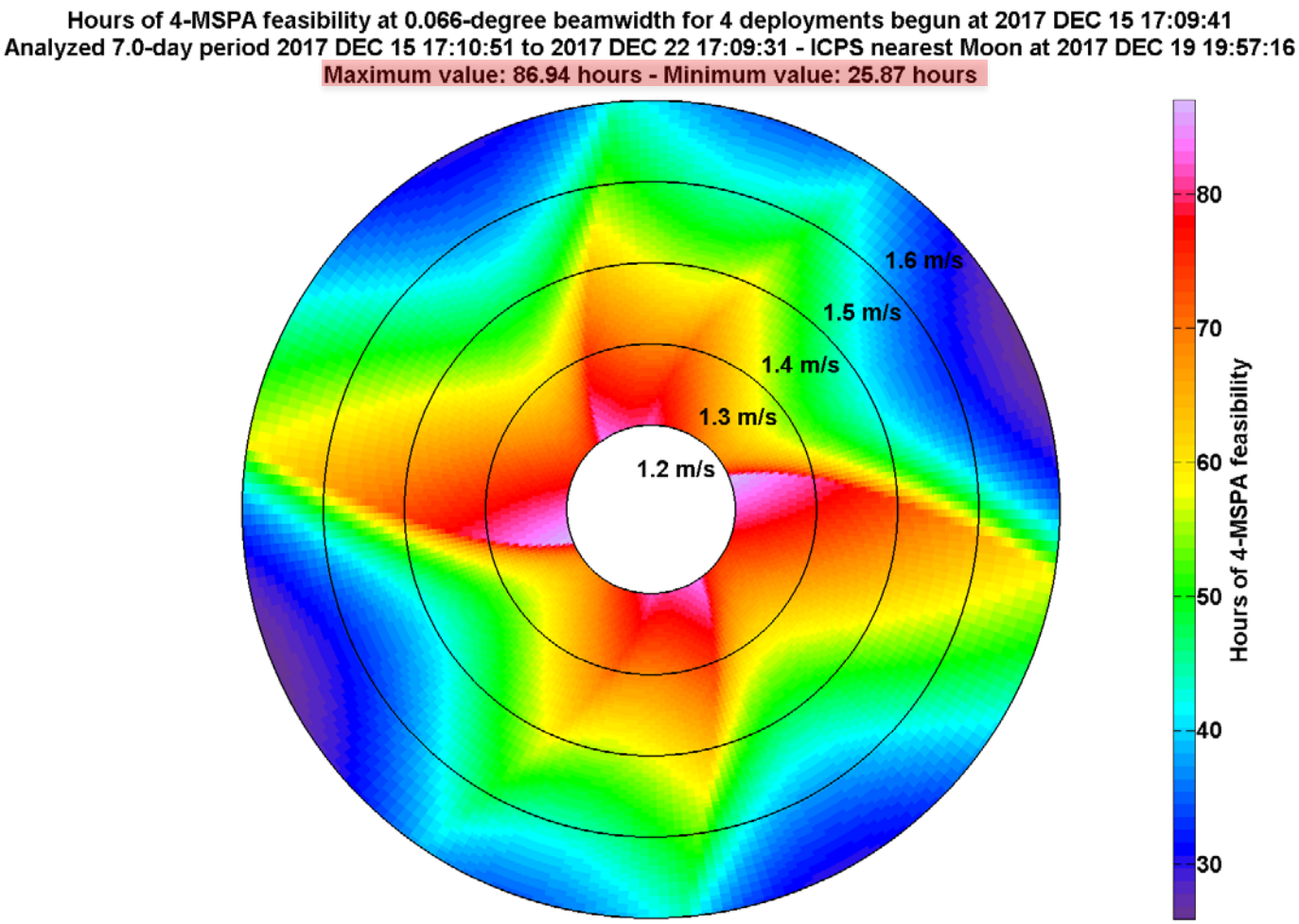
The lunar flyby tends to terminate all otherwise-existing 4-MSPA feasibility by spreading clusters.

Regardless of release direction, as cubesat speed **increases**, 4-MSPA time **decreases** (clusters widen faster.)

Releases at Stop #3, 10-second spacing

The is the “above Van Allen belts” bus stop, about 2 hours after the first bus stop.

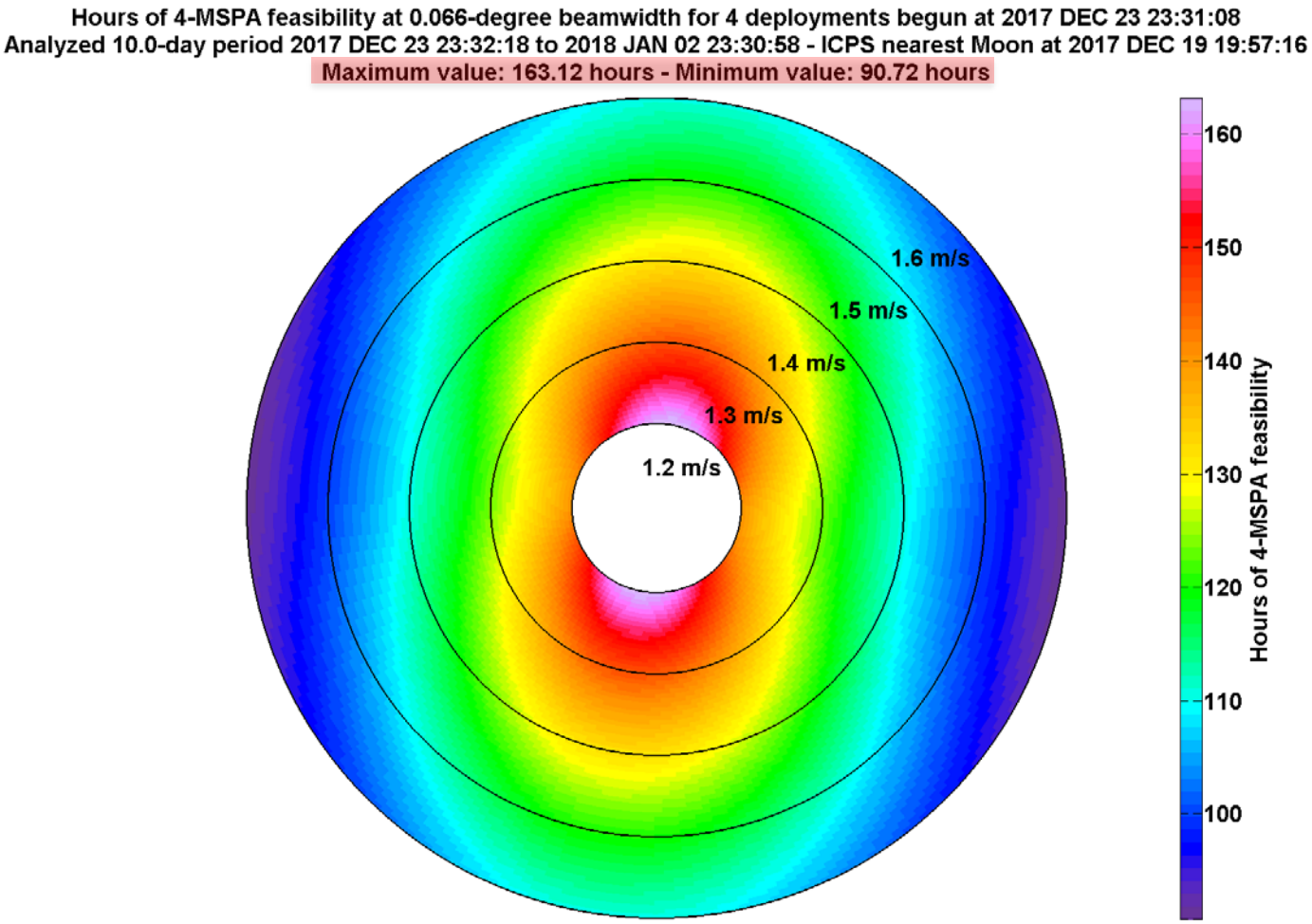
Cubesats numbered 5 through 8 were deployed here.



Releases at Stop #5, 10-second spacing

The is the “end of the line” bus stop, about 4 days after the lunar flyby.

Cubesats numbered 9 through 12 were deployed here.



Tabulated Results

The minimum and maximum values of the 4-MSPA time (over all cubesat speeds and ICPS clockings) are tabulated here for all deployments analyzed:

Bus stop number	Cubesat temporal spacing	Minimum 4-MSPA time	Maximum 4-MSPA time
1	5 seconds	31.9 hours	95.4 hours
1	10 seconds	39.1 hours	100.2 hours
1	30 seconds	50.7 hours	103.1 hours
1	60 seconds	31.5 hours	76.1 hours
3	10 seconds	25.9 hours	86.9 hours
5	10 seconds	90.7 hours	163.1 hours

For deployments far enough from the Moon, **1-2 days** of 4-MSPA time should be feasible. The lunar flyby tends to terminate 4-MSPA.

For deployment well after the lunar flyby, **several days** of 4-MSPA time is likely.

Observations

1. For deployments on the way to the Moon, gravity effects near the Moon usually spread clusters apart and terminate 4-MSPA. The **maximum** possible 4-MSPA duration for a given deployment event is often the time to approach the lunar flyby.

2. For deployments on the way to the Moon, 1-2 days of 4-MSPA coverage should be feasible, but certain deployment configurations **might** provide 4-MSPA longer than **2 days**. Those regions of the possibility space may be small.

3. For any ICPS clock angle, radial-only movement in the performance plots shows increasing 4-MSPA duration with decreasing cubesat release speed: within mission constraints, slower cubesat release speeds tend to be better.

4. For deployments done after the lunar flyby, several days of 4-MSPA time should be achievable.

Questions & Thoughts

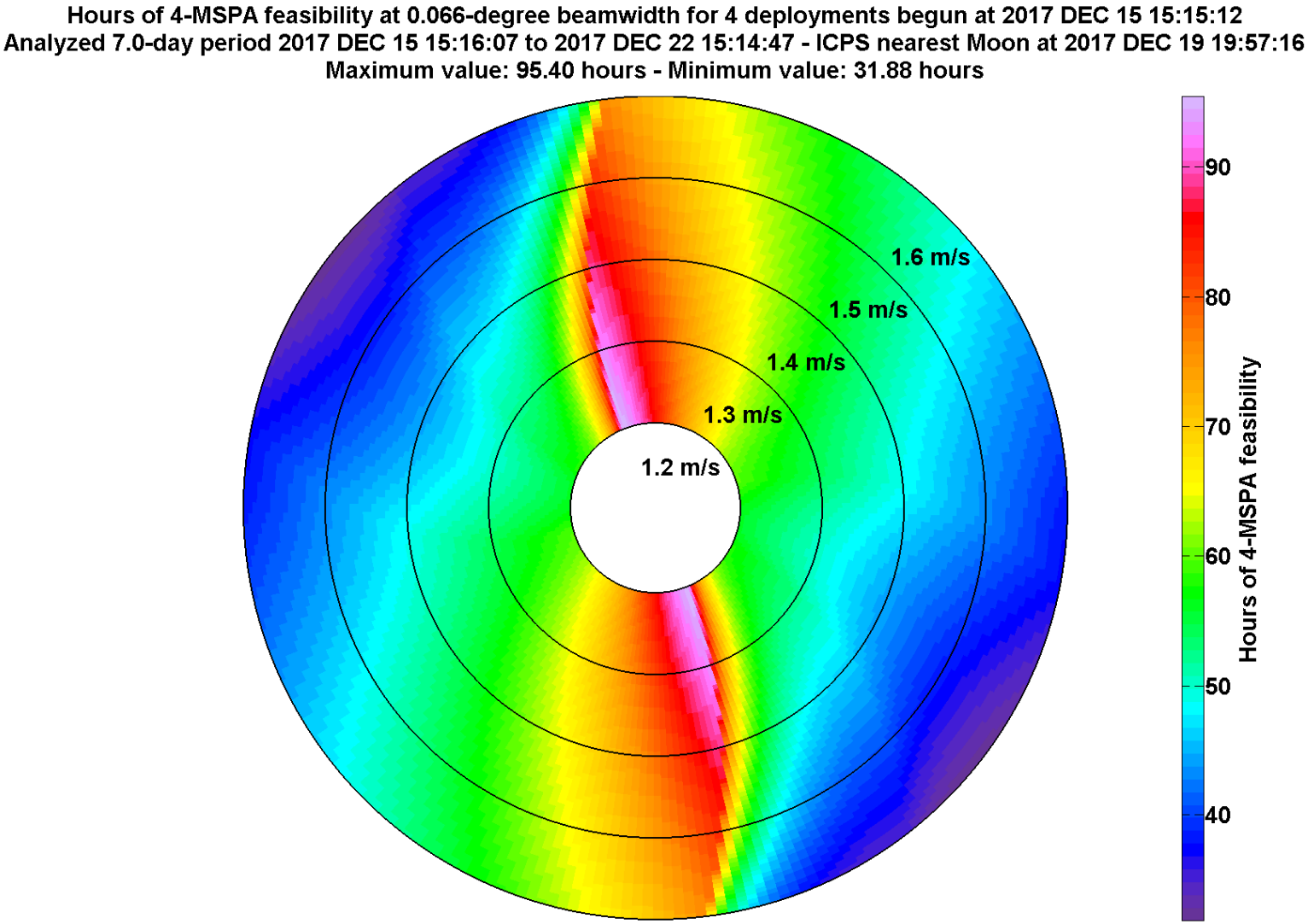
- Could the intervals between releases be adjusted to give cubesats 2, 3, & 4 at a stop the same (or similar) clock angles as the first one? This would keep the clusters closer together longer. Such a timing program could be designed ahead for **any** deployment sequence and guarantees long 4-MSPA coverage. It is **independent** of ICPS clocking at release initiation.

- How robust might these results be to changes in the launch date and ICPS trajectory? Dave's guess: The minimum values are quite robust, the maximum values less so, and the patterns and sensitivities of 4-MSPA duration will be different with changes in trajectory and design.

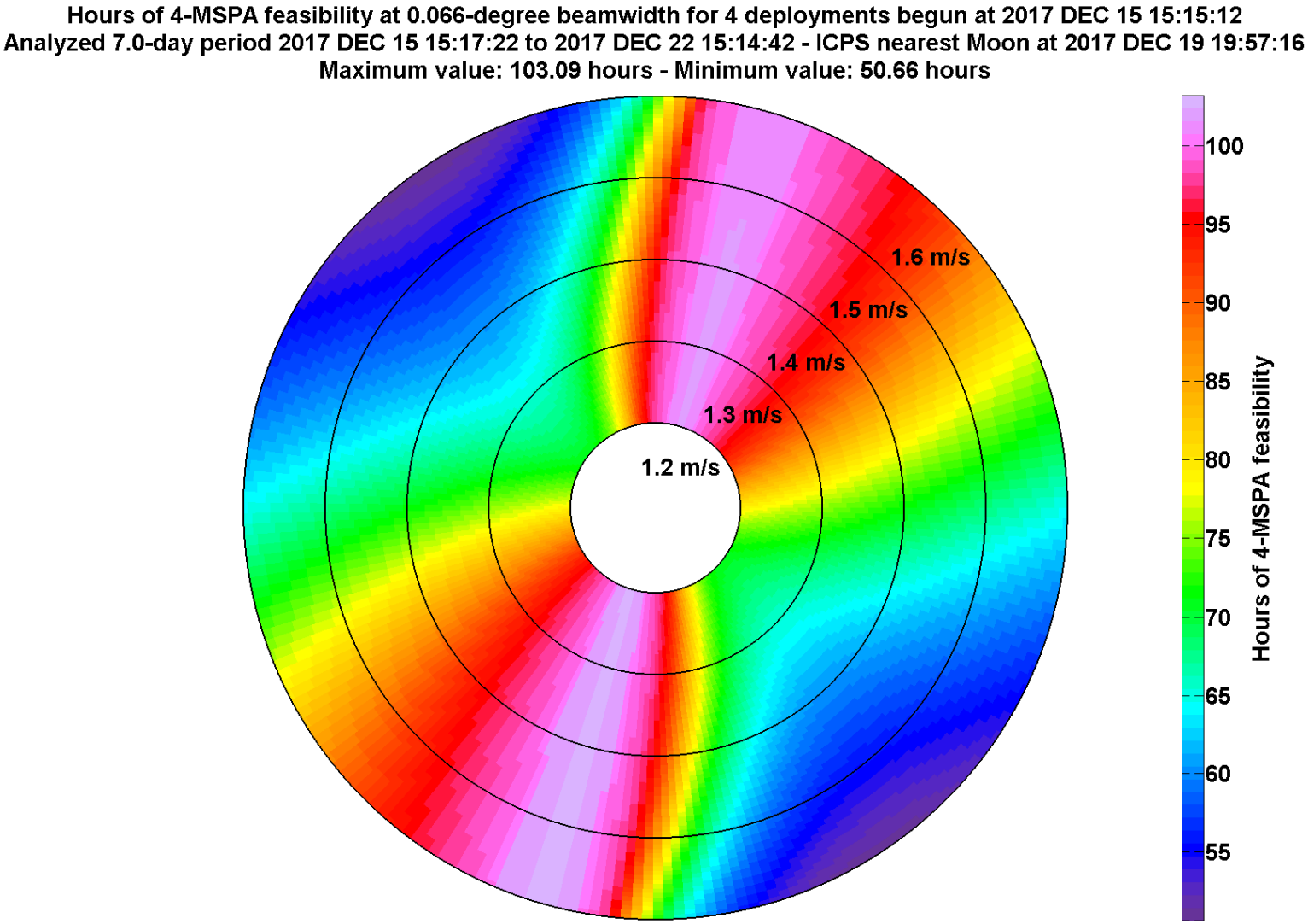
- New EM-1 date/trajectory plans (coming Sept. 2016?) hopefully will also include a new ICPS state vector and epoch.

Additional Plots

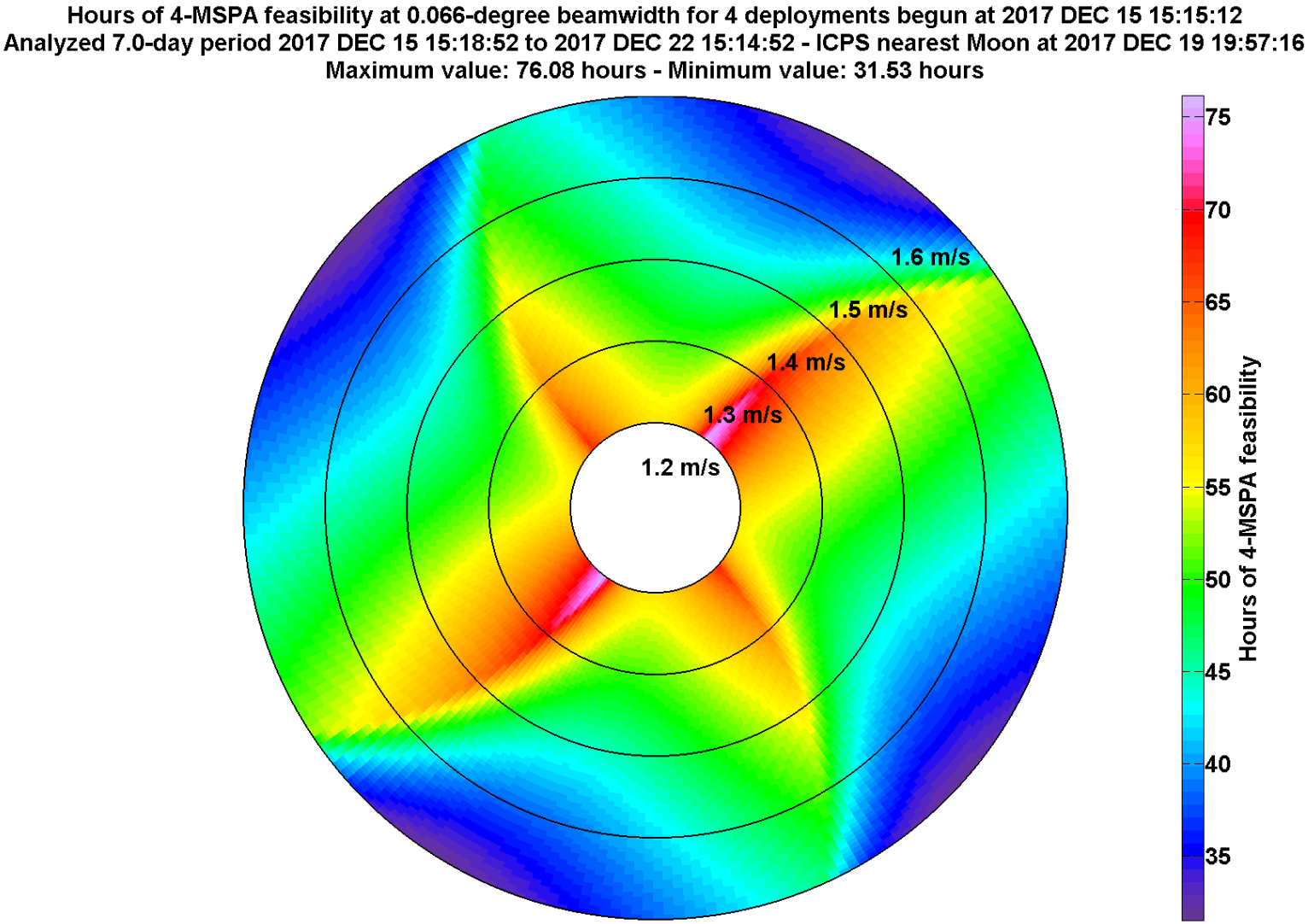
Releases at Stop #1, 5-second spacing



Releases at Stop #1, 30-second spacing



Releases at Stop #1, 60-second spacing



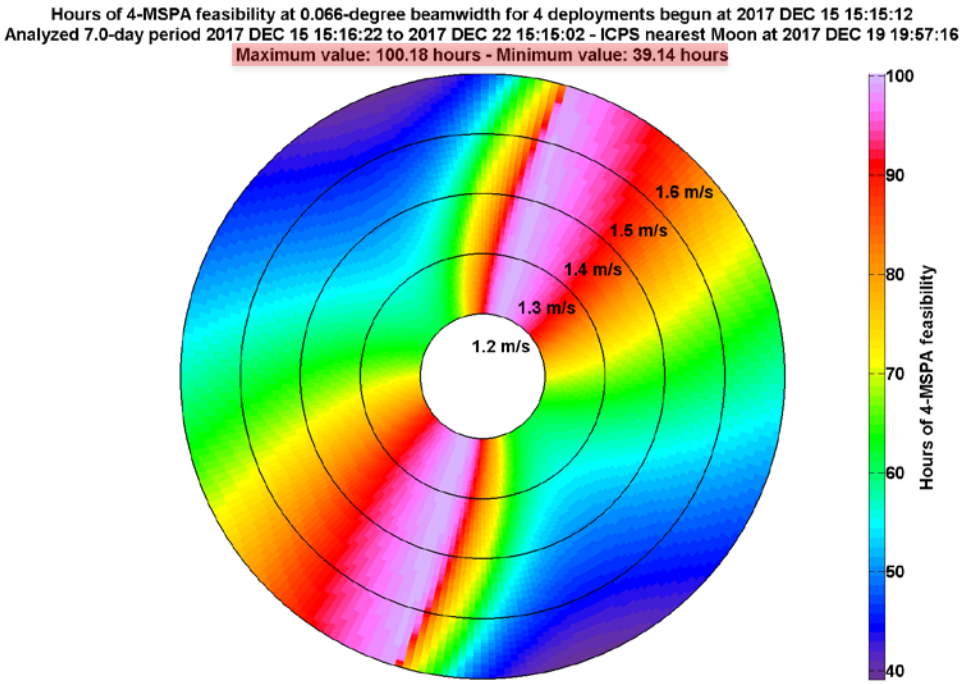
Subsequent Studies

ICPS Rim Speed Contribution

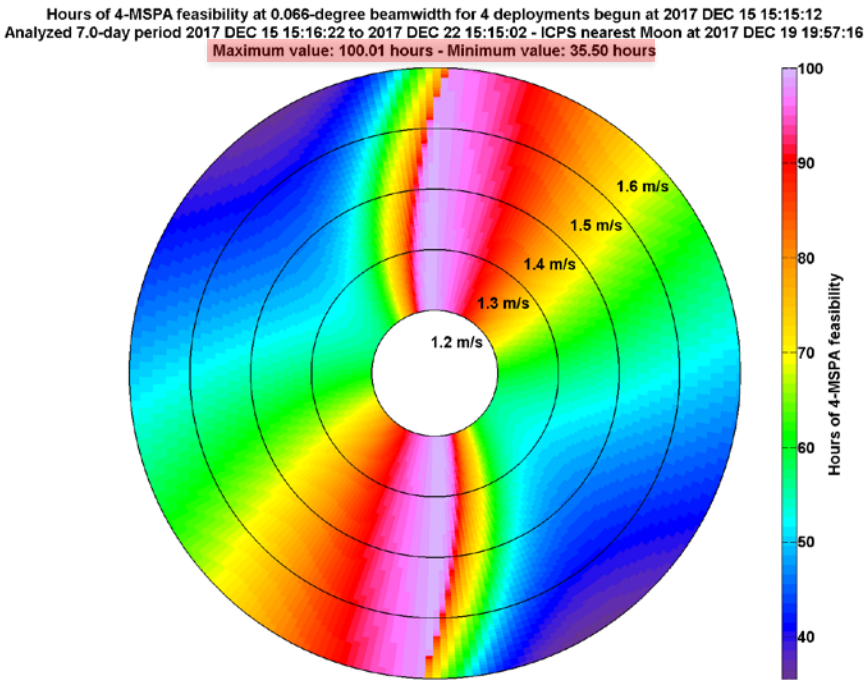
How much does the tangential velocity addition (1 RPM roll) change the answers?

- Evaluated **first** bus stop with **30-second** deployment spacing
- Maximums are essentially identical (recall the lunar flyby cutoff!)
- Minimums are different: 39.14 hours (no rim speed) vs. 35.50 hours
- Not a huge difference here, but might be bigger for other cases

No rim speed accounting

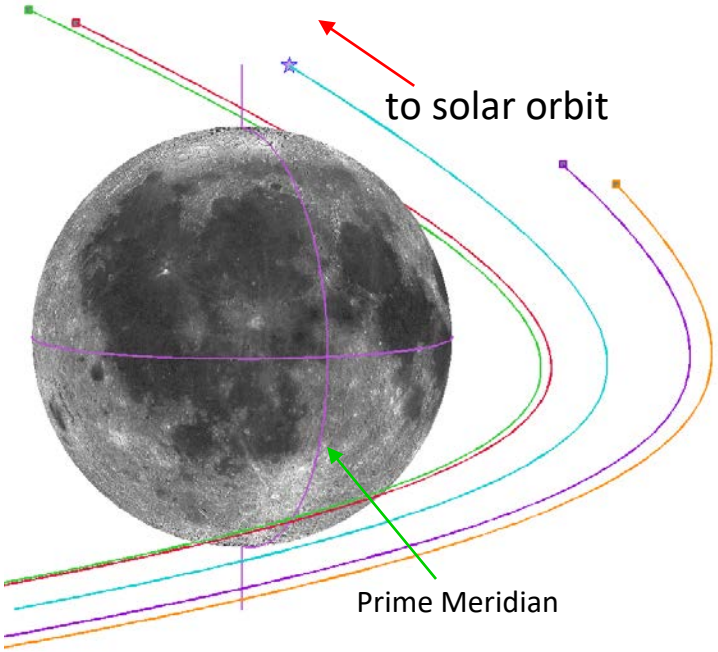


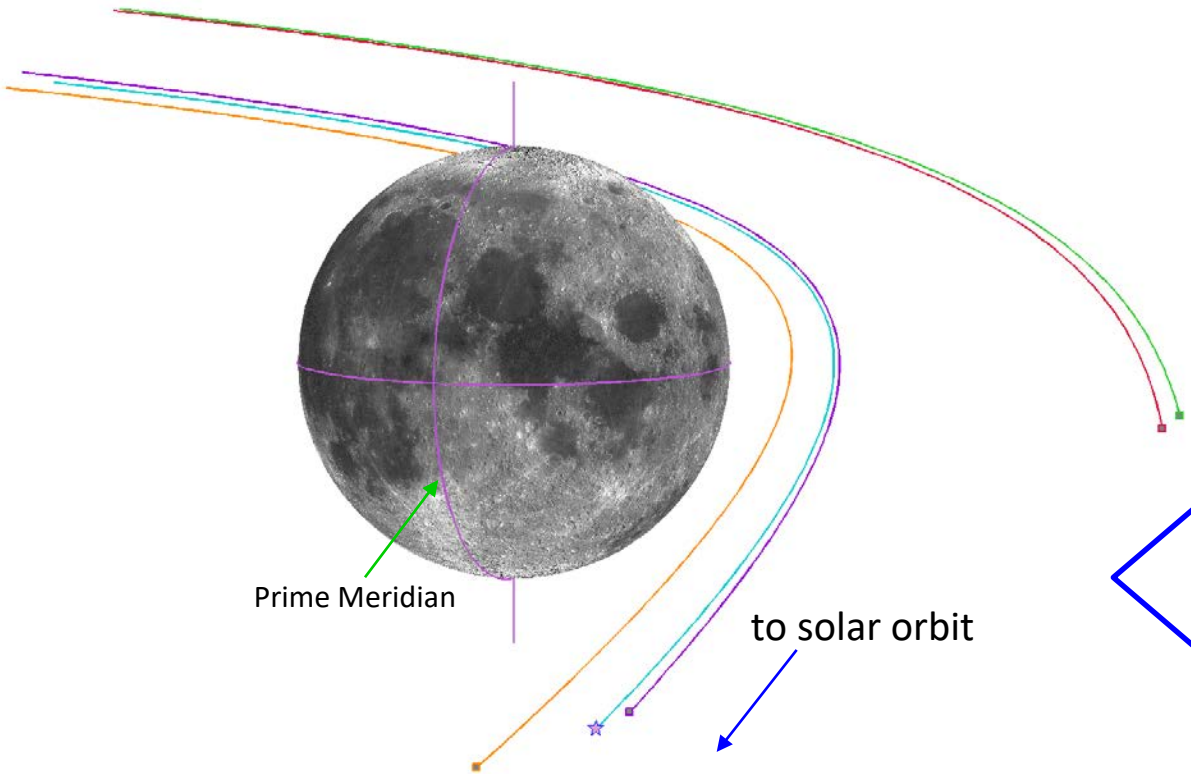
With rim speed accounting



New ICPS Trajectory Model

Original ICPS model: launch 2017 DEC 15, **100.7 hours** from first bus stop to the lunar flyby





New ICPS model: launch 2018 OCT 07, **137.2 hours** from first bus stop to the lunar flyby

Dispersion In Cubesat Speeds, etc.

- Cubesats have varying speeds off their deployers: They are expected to take speeds in the interval (.95,1.6) meters per second.
- The ICPS sweeps uniformly over all clock angles once each minute and its angular orientation at any bus stop is unknown.

Probability is a tool for measuring uncertainty and degree-of-belief.

A probability distribution is a useful model in the presence of unknown values, expected variations, or postulated/observed randomness.

Distribution sample spaces can include undetermined design parameters.

Analysis approach: Draw observations from an appropriate "4MSPA hours" *distribution* built from modeling unknown cubesat speeds spread uniformly over their known range and unknown ICPS clocking on (0,360) degrees. Statistical inference methods will supply percentiles and quantities useful for engineering design.

Toward a 4MSPA Distribution Model

"what I know"	"how I reason"	"what I do"
The ICPS rolls at a *constant* 1 RPM (assumed counter-clockwise.)	Until closer knowledge arrives, whenever a bus stop occurs, its starting deployment angle is equally-likely over all possible values.	Model the ICPS initial-angle distribution at any bus stop as *Uniform*(0,360) random variable.

…and probabilistically independently…

Cubesat release speeds vary with masses, springs, and issues. Each cubesat can have a speed in the interval (.95,1.6) meters/sec.	Without additional data, no biases exist that would favor certain speeds over others. Each cubesat could launch with any speed in the feasible interval.	Model each cubesat speed as an independent *Uniform*(.95,1.6) random variable.

Note that each of the distributions could be updated if new/better data arrived or different assumptions needed to be incorporated.

Analyzing the 4MSPA Distribution

The (extremely complicated!) distribution of feasible 4MSPA hours is addressed using computational statistical methods.

For a given bus stop and cubesat temporal spacing…

Generate input random variables

- Draw an ICPS angle uniformly randomly from (0,360) degrees
- Independently draw 4 cubesat speeds uniformly randomly from (.95,1.6) degrees

Compute a 4MSPA hours random variable outcome

- Put the ICPS angle and 4 different cubesat speeds into the 4MSPA hours computational engine.
- The computation's outcome is **one** observation of the 4MSPA hours random variable.

Amass observation pool, compute sample statistics

- Repeat the above two steps to draw the largest pool of 4MSPA hours observations your resources allow (12000 per bus stop and per cubesat temporal spacing in this study)
- Compute sample statistics of interest from this pool
- Confidence intervals and measures of estimator accuracy can also be derived

The outcome of this process is **useful** inferences drawn over the combined sample space of non-fixed design parameters and explicitly random phenomena, *conditioned* on the known data.

4MSPA Percentiles – First Trajectory

Percentiles (in **hours** of 4MSPA feasibility) of the 4MSPA distribution for the **first** ICPS trajectory model:

		Launch Spacing	Minimum	5th	10th	15th	50th	75th
"system initiation"	**Bus stop 1, cubesats 1-4**	10 seconds	35.08	42.32	45.61	48.15	64.95	84.45
		30 seconds	40.12	50.23	53.03	55.58	73.69	92.30
		60 seconds	28.43	35.23	37.77	39.81	51.09	59.10
"clear of Van Allen belt"	**Bus stop 3, cubesats 5-8**	10 seconds	23.59	34.29	37.45	40.05	55.65	68.00
		30 seconds	82.74	93.89	95.03	95.63	97.26	98.24
		60 seconds	20.36	28.38	31.73	34.65	59.79	75.68
"end of the line"	**Bus stop 5, cubesats 9-12**	10 seconds	87.14	97.53	101.09	103.75	117.53	131.26
		30 seconds	168.00	198.09	208.21	216.65	270.17	317.72
		60 seconds	87.95	97.42	100.97	103.55	114.63	126.22

Example: The 5th percentile value is one associated with a probability of .05 of being **smaller** and 1-.05=.95 of being **larger**. There is a **95%** probability of having **more** time in 4MSPA than the marked column's values.

The 50th percentile is the **median** of the distribution.

4MSPA Percentiles – Second Trajectory

Percentiles (in **hours** of 4MSPA feasibility) of the 4MSPA distribution for the **second** ICPS trajectory model:

	Launch Spacing	Minimum	5th	10th	15th	50th	75th
Bus stop 1, cubesats 1-4	10 seconds	29.60	33.76	35.82	37.63	49.38	69.11
	30 seconds	34.68	40.89	43.15	44.98	59.44	89.99
	45 seconds	27.45	30.43	32.35	34.15	46.02	57.50
	60 seconds	27.32	29.38	30.53	31.56	38.20	43.62
Bus stop 3, cubesats 5-8	10 seconds	23.95	33.20	35.60	37.30	45.51	53.51
	30 seconds	91.48	126.43	134.53	134.64	135.07	135.65
	45 seconds	21.59	29.87	32.33	34.05	42.13	49.90
	60 seconds	20.90	27.76	30.44	32.52	40.76	48.59
Bus stop 5, cubesats 9-12	10 seconds	37.69	44.08	46.58	48.69	69.55	100.61
	30 seconds	79.55	106.83	117.73	126.47	176.92	221.05
	45 seconds	39.40	47.00	49.52	51.67	66.47	81.09
	60 seconds	38.13	44.26	46.50	48.16	60.25	77.27

Note the performance with 30-second spacing!

For this trajectory model (and other parameters), there is a **95%** probability of getting **more** hours of 4MSPA time than values in this column.