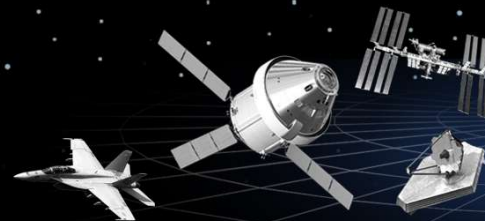


NESC L&D TDT F2F May 2022



NESC Support Of Double Asteroid Redirection Test (DART) Mission

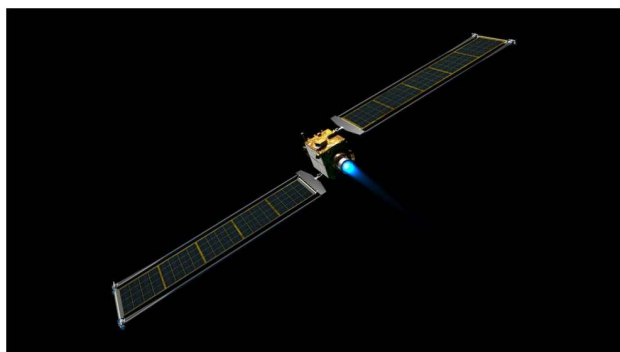
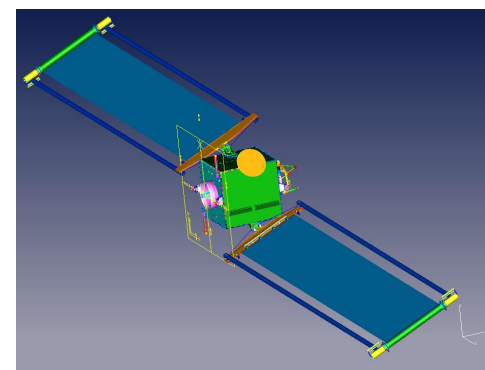


Illustration of the DART spacecraft with the Roll Out Solar Arrays (ROSA) extended. Each of the two ROSA arrays is 8.6 meters by 2.3 meters.



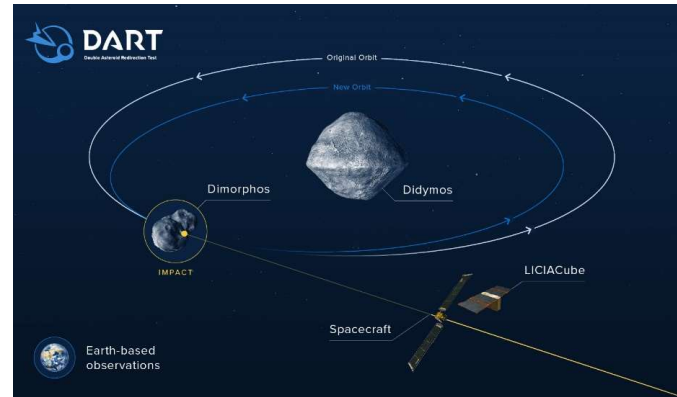
James Akers: NASA GRC Structural Dynamics Branch
Matt Chamberlain: NASA LaRC Structural Dynamics Branch

May 18, 2022

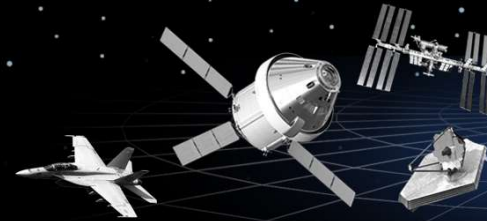
DART Mission Objective



- DART is NASA's first mission to demonstrate asteroid deflection by a kinetic impactor (planetary defense).
 - Managed and integrated by Johns Hopkins University Applied Physics Laboratory (APL).
 - Launched 10:21 pm PST, Nov 23, 2021, aboard a SpaceX Falcon 9 rocket from Vandenberg Space Force Base, CA.
 - Scheduled to impact asteroid Didymos' moonlet Dimorphos on September 26, 2022.



DART Mission Video

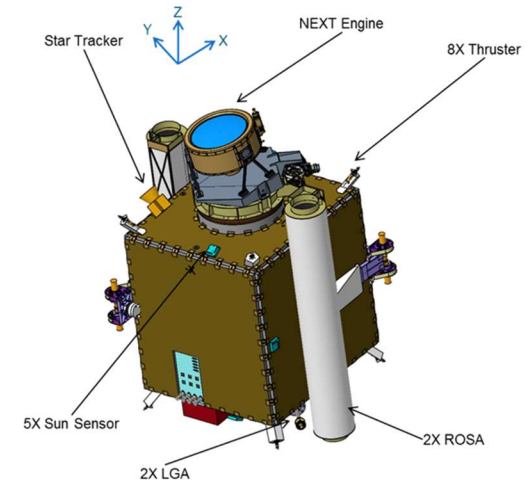
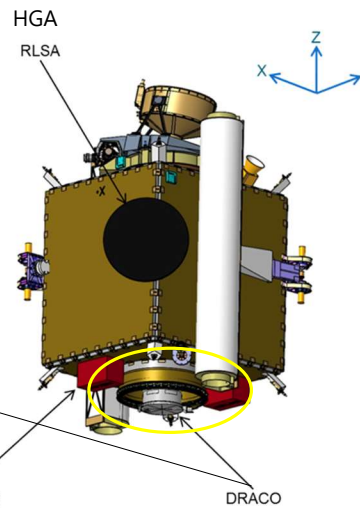


Video of DART ROSA
Solar Array:
<https://www.youtube.com/watch?v=7Rzuk95qS0w&t=70s>

DART Spacecraft



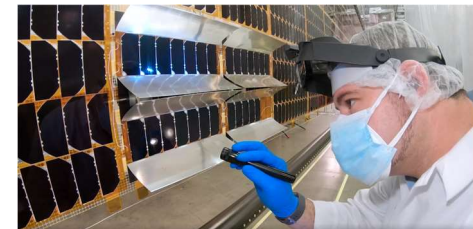
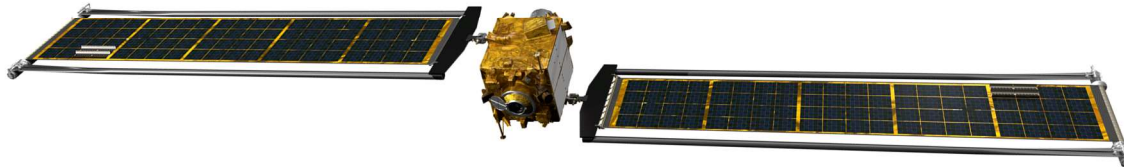
- Launch mass of 610 kg (1345 lbm) and impact mass of 550 kg (1,210 lbm).
- Johns Hopkins University Applied Physics Laboratory (APL) built the Didymos Reconnaissance and Asteroid Camera for Optical navigation (DRACO) that will not only capture images of Didymos and Dimorphos, but also support autonomous optical navigation for the DART spacecraft.



DART Spacecraft (cont)



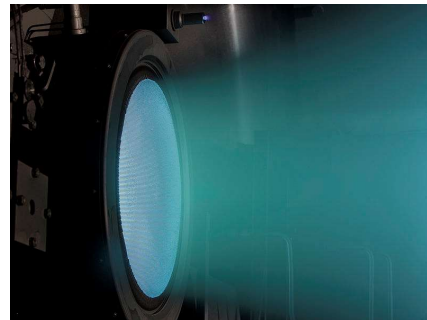
- Central spacecraft body is a roughly 1.3 m (4.3 ft) cube, which has two Deployable Space Systems (DSS/Redwire) Roll-Out Solar Arrays (ROSA) each 8.6 m (28.2 ft) long and 2.3 m (7.5 ft) wide.
 - First time used in deep space.
 - Featuring powerful APL-developed Transformational Solar Array concentrators.
 - Provides a total of 6.6 kW of power at Beginning Of Life (BOL).
 - A small portion of the DART solar array is configured to demonstrate Transformational Solar Array technology, which has very-high-efficiency solar cells and reflective concentrators providing three times more power than current solar array technology.



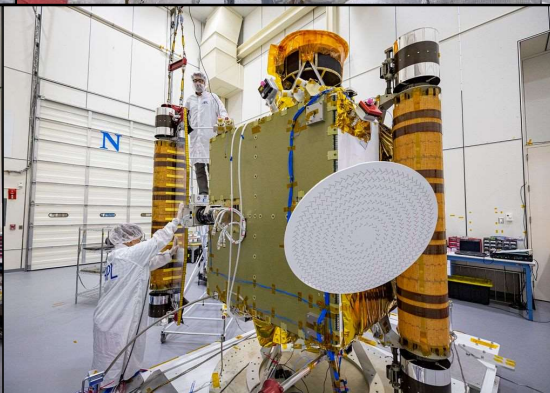
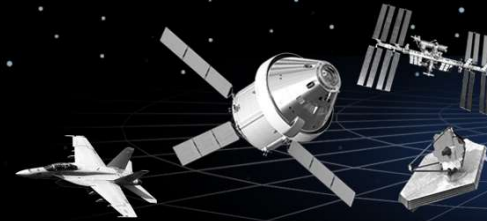
DART Spacecraft (cont)



- The ROSA solar arrays power NASA's Evolutionary Xenon Thruster — Commercial (NEXT-C) ion engine.
 - Developed by Glenn Research Center in collaboration with Aerojet Rocketdyne.
 - DART also has hydrazine chemical thrusters for maneuvering and attitude control.



DART Spacecraft Integration

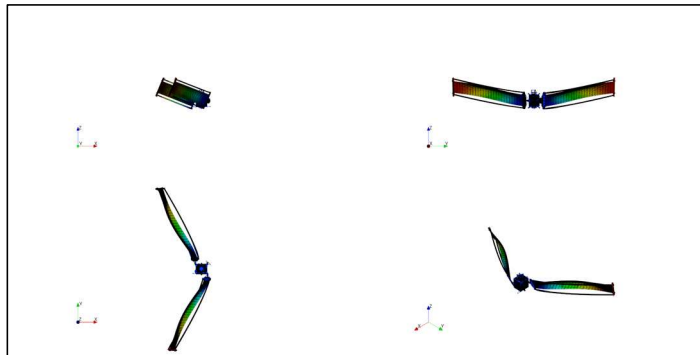


DART Spacecraft Dynamics

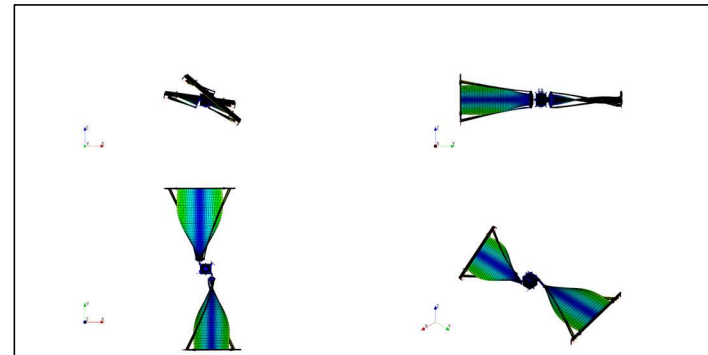


- DART spacecraft low frequency dynamics dominated by the ROSA solar arrays.

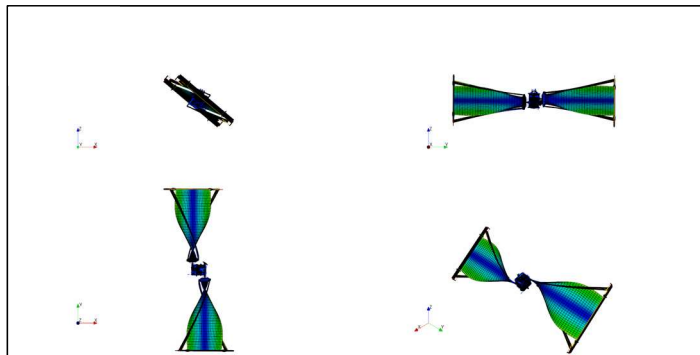
Free Elastic Body #1:
1st bending of the ROSA
Slit Booms in-phase.



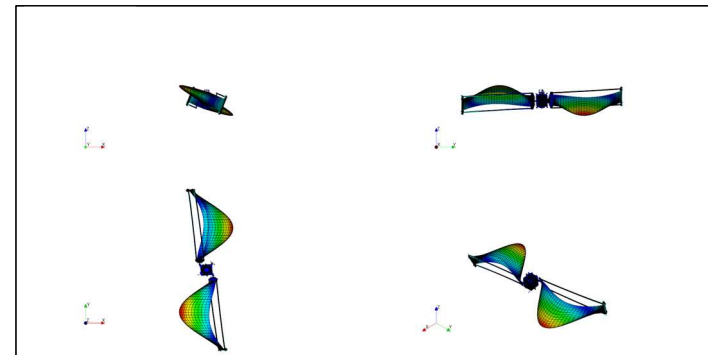
Free Elastic Body #2:
1st torsion of the ROSA's
out-of-phase.



Free Elastic Body #3:
1st torsion of the ROSA's in-
phase.



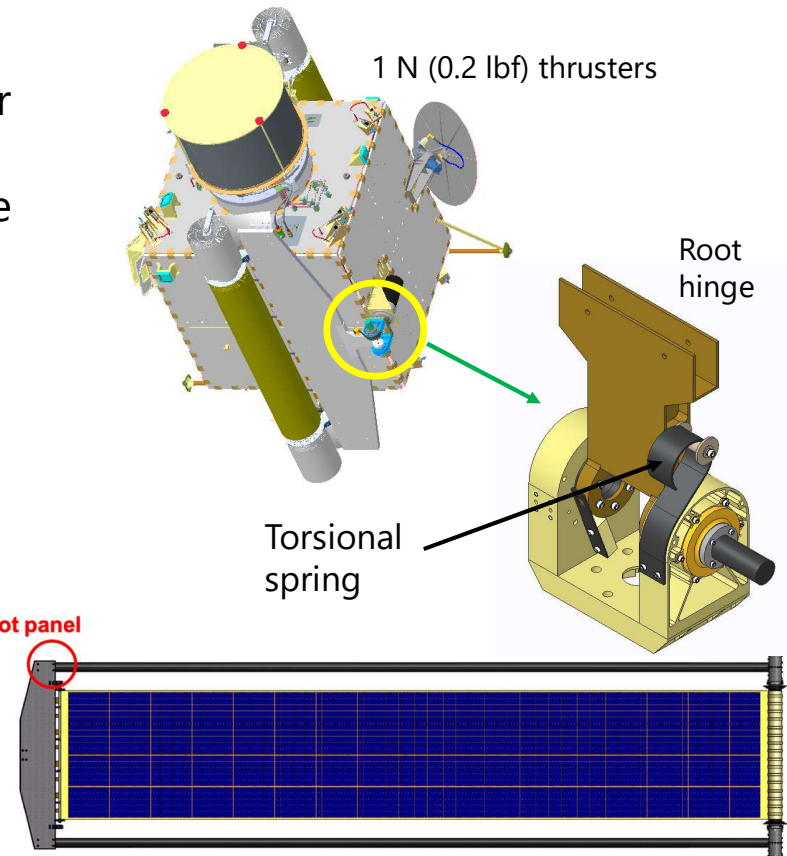
Free Elastic Body #4:
1st bending of the ROSA
solar array blankets out-of-
phase.



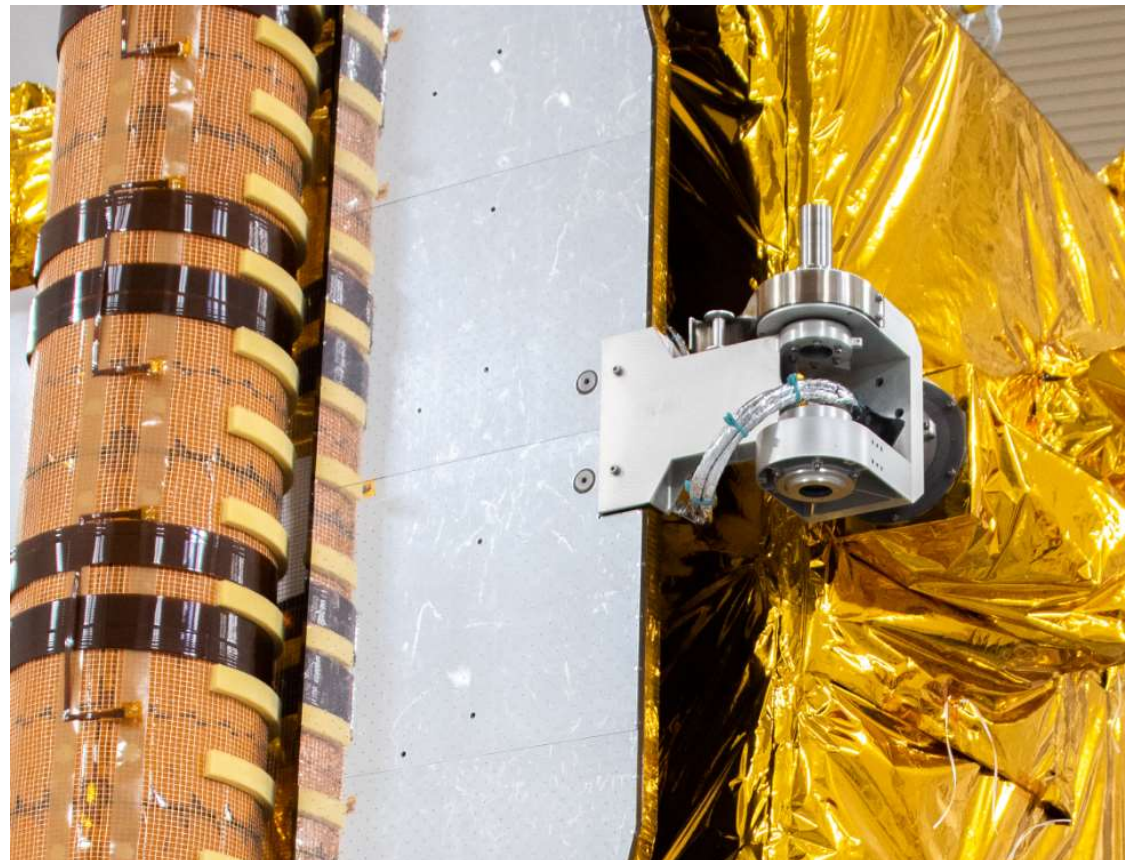
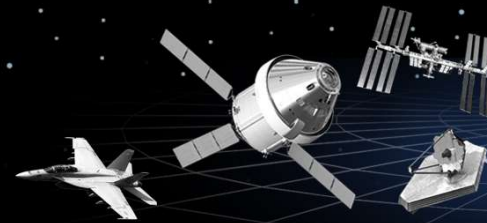
Late Breaking Solar Array Concerns



- Johns Hopkins University Applied Physics Laboratory (APL) shortly before launch analytically predicted higher than expected loads with their Guidance Navigation and Control (GN&C) model at the solar array root hinge during maneuvers such as the Trajectory Correction Maneuvers (TCM's).
 - Instability concern.
 - Also concern of damaging the solar array itself.
 - Most vulnerable point of the solar array was believed to be at the junction between the slit boom and the root panel
 - Suspected that post-processing techniques use to extract loads from the GN&C simulations were not accurate.



DART ROSA Root Panel & Hinge In Stowed (Launch) Configuration



5/18/2022

NESC L&D TDT F2F DART

10

Primary Load Event



- APL particularly concerned about ROSA loads during first Trajectory Correction Maneuver (TCM1).
 - Occurs approximately 5 months after launch and is the biggest delta-V maneuver.
 - Duration, level, and orientation of the ROSA solar arrays highly variable and dependent upon the launch.
- TCM's can be minutes to hours long.
- Because the orientation of the solar arrays affects the amount of power they generate, APL wanted to avoid rotating them from the desired orientation (i.e., feathering) unless absolutely necessary.

Timeline



- APL reached out to NASA GN&C Technical Fellow Cornelius Dennehy on 11/03/21 (L-21) about concerns of loads into the ROSA solar array and its root hinge.
- Cornelius Dennehy reached out to NASA L&D Technical Fellow Dexter Johnson on 11/05/21 requesting an L&D expert to peer review the APL solar array modes.
- NESC involvement included supporting five meetings with APL from 11/09 (L-15) through 11/22 (L-2), performing independent force response analyses, and comparing NESC and APL displacement results at key locations on the spacecraft at the 11/22 (L-2) meeting in support of the launch go/no-go decision.
 - Very aggressive schedule due to unfamiliarity with the model and forcing function.

NESC Proposed Recommendations 1



- APL assemble DART loads models for pertinent flight configurations (i.e., different ROSA orientations and propellant levels).
- APL apply their GN&C thruster force time histories to their assembled DART loads models.
- APL supply NESC with a DART loads model and a GN&C Attitude Control Maneuver (ACM) thruster force time history and NESC independently compute displacements at selected key locations.
 - NESC compare NESC and APL GN&C model displacements.

NESC Proposed Recommendations 2

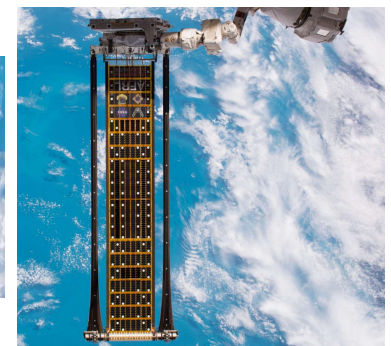
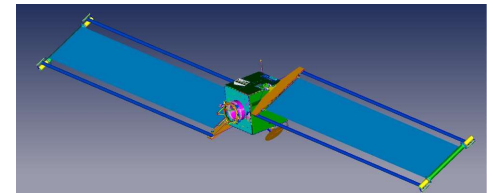


- Assuming NESC, APL's GN&C model, and APL's loads model displacements are in good agreement, APL use the loads generated by their assembled DART loads models going forward.
 - This only verifies APL is appropriately applying thruster forces to their loads model.
 - Unfortunately, insufficient time available to verify APL's loads model.
- Science Mission Directorate (SMD) Chief Engineer (CE) Nicholas Jedrich at 11/09/21 meeting also recommended APL perform a sensitivity analysis to try and better understand model uncertainty.
 - Status of sensitivity analysis unknown.

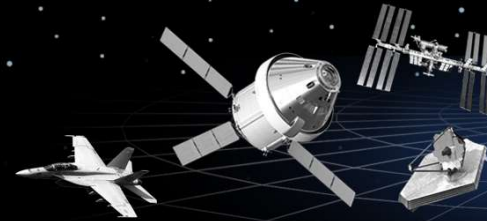
NESC Independent Force Response Analysis



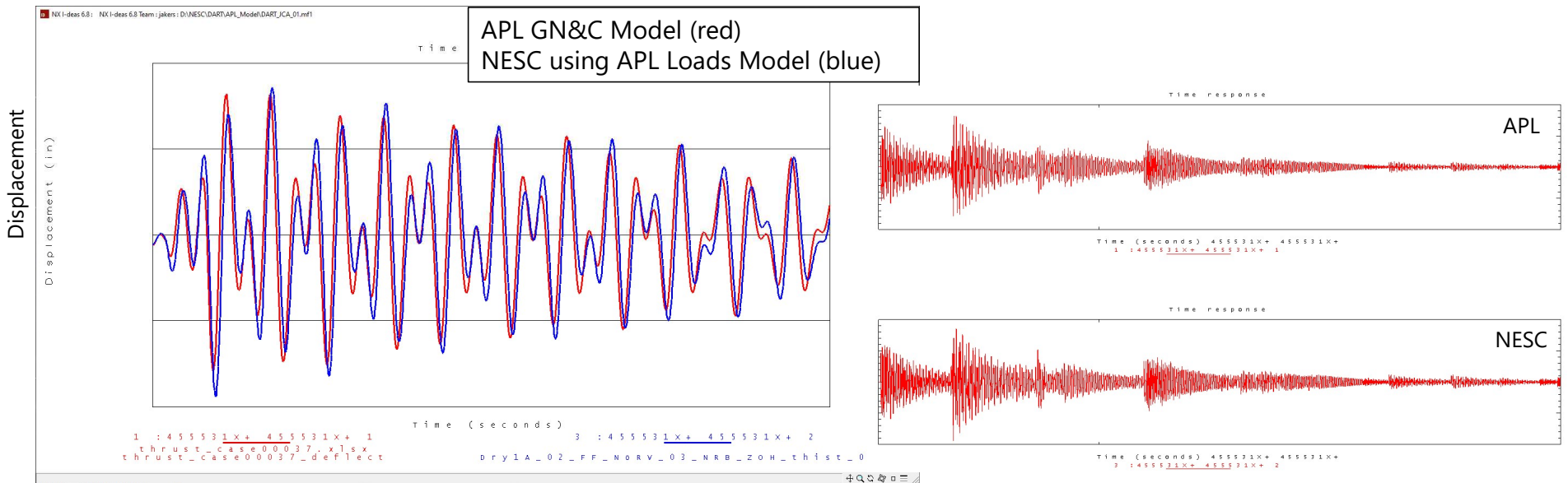
- NESC received a DART FEM, GN&C ACM thruster force time histories and associated DART GN&C model deflection on 11/12/22.
- The NESC had two teams independently perform force response analyses with the APL provided models and data.
 - NASA LaRC: Matthew Chamberlain, Lucas Horta, and Mercedes Reaves.
 - Utilized an in-house spacecraft attitude control software package.
 - Matthew Chamberlain has extensive knowledge of ROSA solar array properties from being involved with the ROSA Flight Experiment.
 - NASA GRC: James Akers.
 - Utilized Ideas, Matlab, IMAT, and MSC Nastran.



APL & NESC Displacement Comparison



- Very good agreement between APL GN&C model, APL loads model, and NESC displacements at both the spacecraft body and the ROSA, both in terms of peak values and frequency content.



Summary

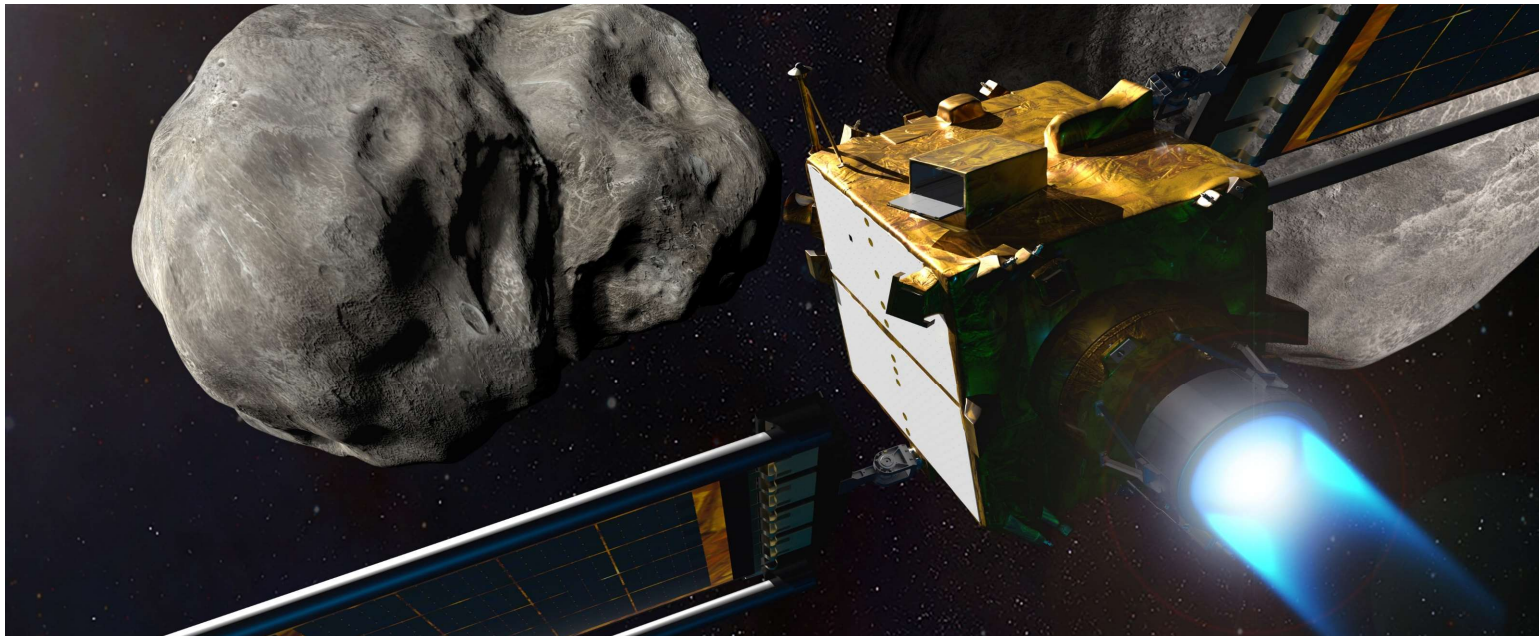


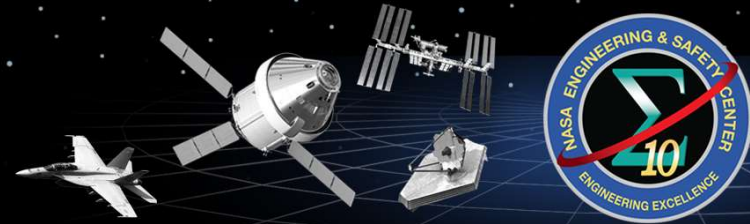
- Very good agreement between APL GN&C model, APL loads model, and NESC displacements at both the spacecraft body and the ROSA, both in terms of peak values and frequency content verified for the provided ACM thruster force time histories:
 - APL GN&C model displacements were consistent with the APL loads model displacements. ✓
 - Unfortunately, does not validate the APL GN&C or loads model. ☹️
 - The very small peak displacements compared to the maximum displacements seen during ground static testing indicate that ACM thruster firings should pose a low risk of damaging the ROSA solar arrays or overcoming their root hinge holding torque that could cause flight control system instability. ✓✓

Forward Work



- While the NESC has not been tasked with any further work at this time, it remains ready to assist the DART program if needed.





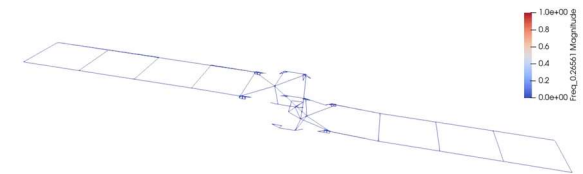
Backup Slides

LaRC Approach

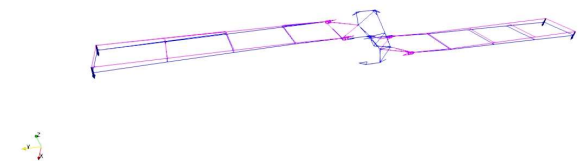


- APL model imported into Abaqus, found to be too large to do anything.
- APL model imported into NASTRAN for model checks to check model, compare modes with APL predictions, and check simple static loads cases.
 - Modes compared favorably with APL predictions.
 - Static loads product wing-tip deflections similar to boom bending test results.
- Mass, stiffness, mode shapes imported into Matlab, used in existing control loop simulation for expediency (later re-run with similar results in Matlab "lsim" function).
 - Known thruster firings simulated with algorithm meant to keep spacecraft in steady orientation.
 - High gains used to remove rigid body motion resulted in tip displacements similar to APL predictions.

First Structural Mode



Array Deflections Similar to Ground Test



GRC Approach 1

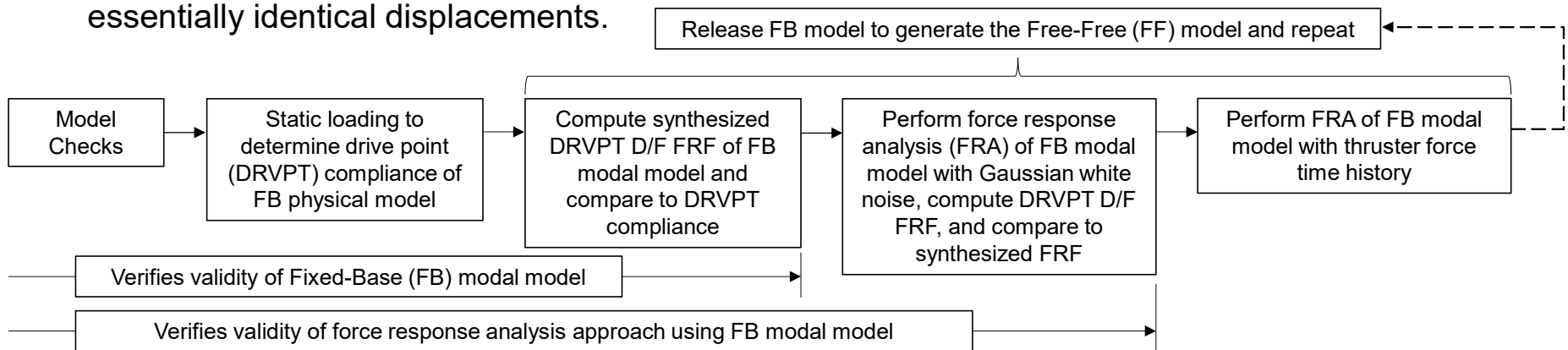


- Ideas Test & Simulation used to investigate the DART loads FEM, animate mode shapes, display Thruster Force and Deflection grid point locations, display time histories, process time histories into FRF, Coherence, and PSD, and plot FRF, Coherence, and PSD.
- MSC Nastran used to perform the standard model checks of free-free and fixed-base modes (SOL 103), 0.1g gravity loading (SOL 101), and compute displacements due to static loading (SOL 101).
- Matlab/IMAT used to animate mode shapes, create movies of mode shape animations, synthesize FRF from mode shapes computed in MSC Nastran, and perform force response analysis using Matlab LSIM function with a modal state-space model.
- MSC Nastran SOL 112 Modal Transient Analysis used to perform force response analysis recovering displacements on the spacecraft and ROSA solar arrays, and loads at the root hinge.
- The affect of sampling interval and the number of retained elastic body modes upon the accuracy of the displacements, velocities, and accelerations was investigated.

GRC Approach 2



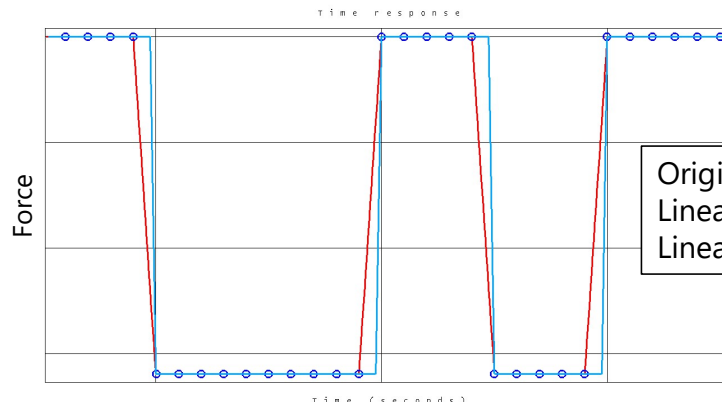
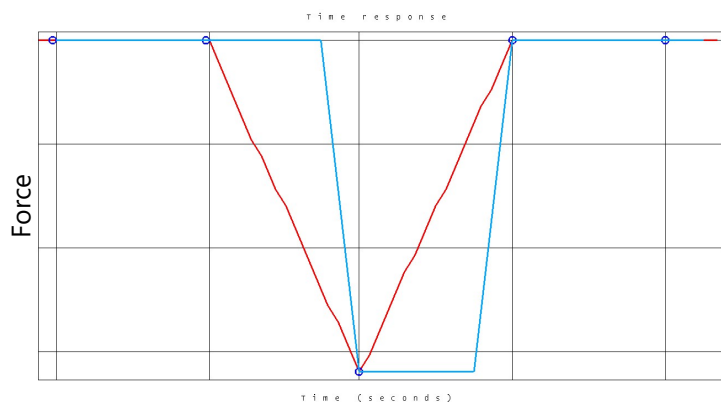
- The affect of converting APL supplied the Thruster Force time histories to a higher sampling frequency was also investigated.
 - Higher sampling frequency was necessary for accurate digital simulations.
 - Linear Interpolation.
 - Linear interpolation with a zero-order-hold (ZOH) mimicking the approach used in the APL DART GN&C simulation.
 - For the sampling frequency chosen the two Thruster Force conversion approaches yielded essentially identical displacements.



GRC Conversion of APL Thruster Force Time Histories

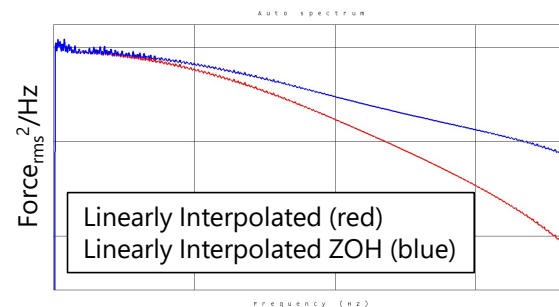


- Note that the linearly interpolated Thruster Force pulse trains have the same area as the "square wave" of the linearly interpolated with ZOH Thruster Force pulse trains.



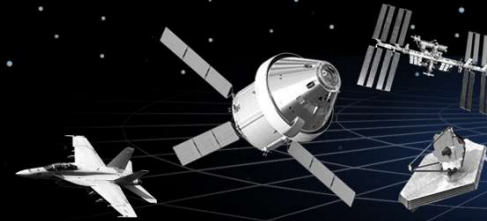
Original (blue circles)
 Linearly Interpolated (red)
 Linearly Interpolated ZOH (It blue)

- PSD magnitudes of these two Thruster Force time history conversions agree very well at low frequency.

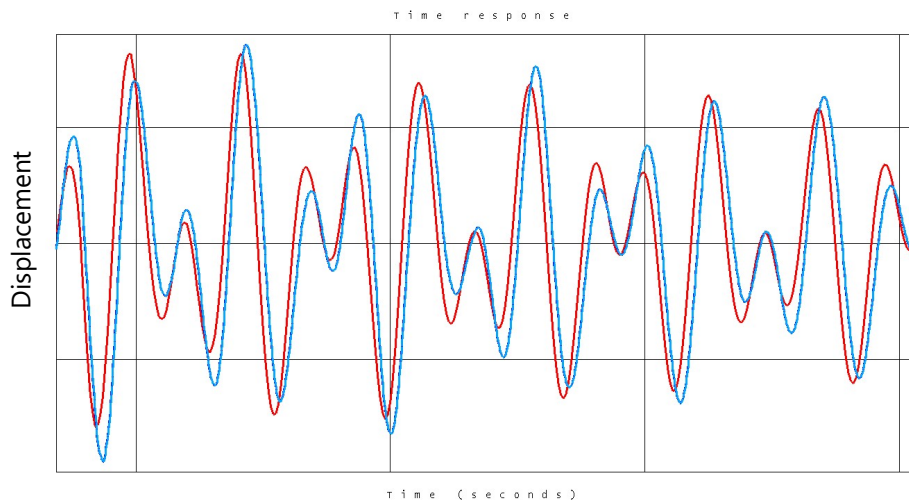


Linearly Interpolated (red)
 Linearly Interpolated ZOH (blue)

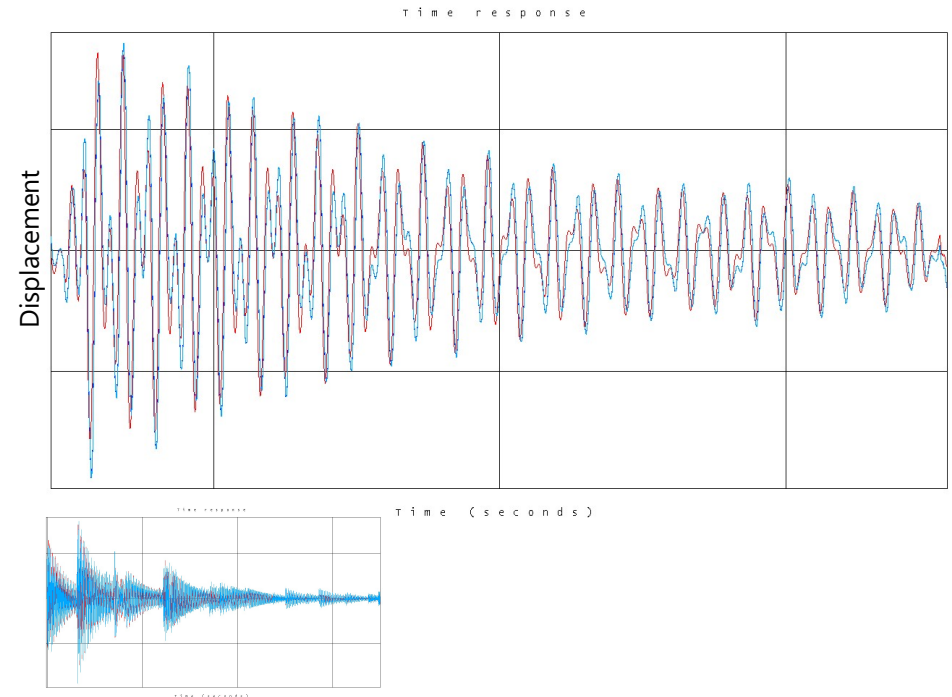
APL vs GRC Displacement Comparison



- Very good agreement between APL and GRC displacements at both the spacecraft body and the ROSA, both in terms of peak values and frequency content.

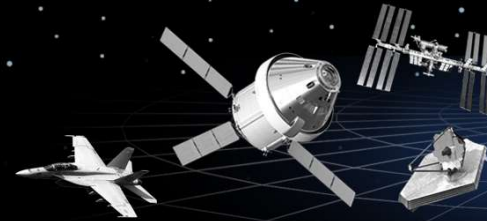


APL Disp (red)
GRC Disp w Lin Interp Thruster Forces (blue)
FRA Disp w Lin Interp ZOH Thruster Forces (lt blue)

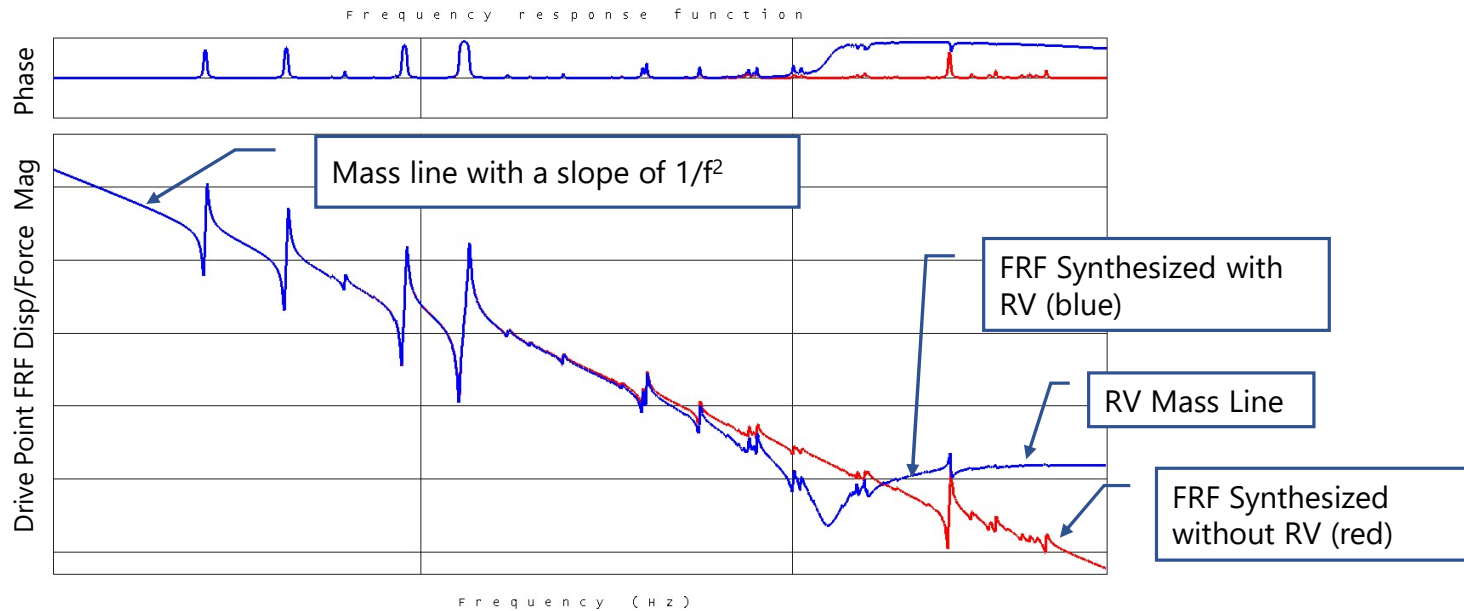




Residual Vectors: Friend or Foe 1



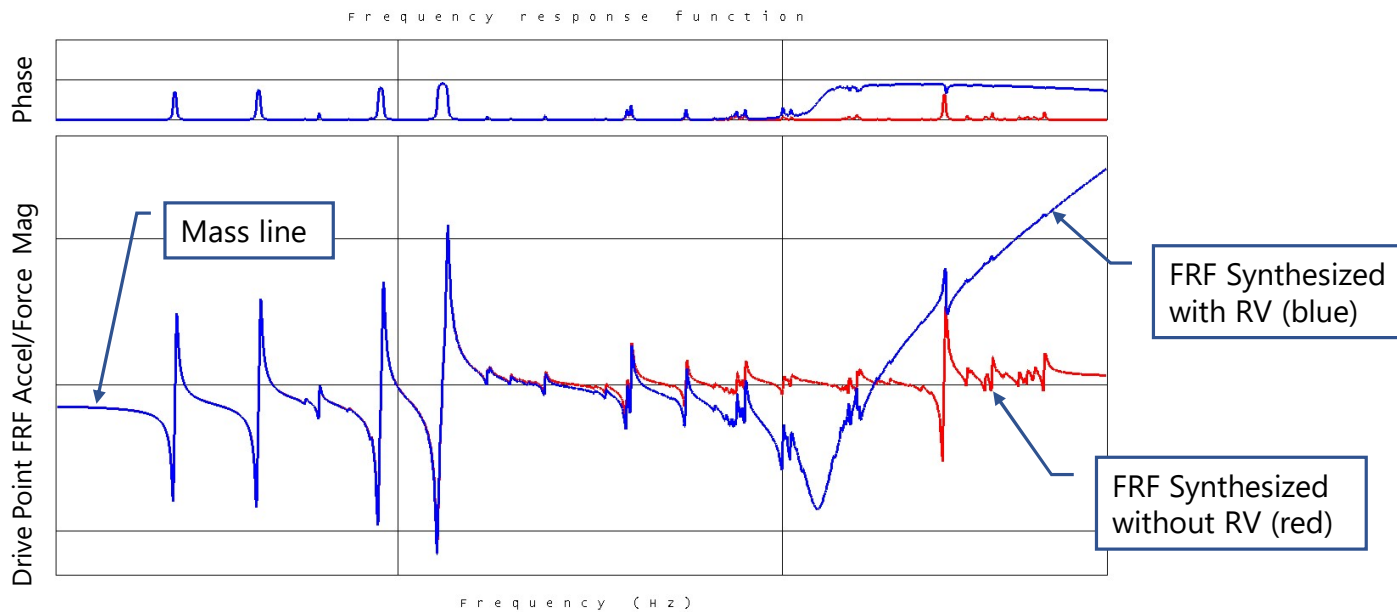
- GRC discovered while residual vectors (RV) significantly improved the accuracy of force response analysis when the spacecraft was fixed, RV decreased the accuracy when the spacecraft was free.



Residual Vectors: Friend or Foe 2



- GRC discovered while residual vectors significantly improved the accuracy of force response analysis when the spacecraft was fixed, but decreased the accuracy when the spacecraft was free.



DART Videos 1



- Video “Behind the Scenes: Inspecting the DART’s Roll-Out solar Array (ROSA) Technology:
<https://www.bing.com/videos/search?q=ISS+ROSA+solar+array&ru=%2fvideos%2fsearch%3fq%3dISS%2bROSA%2bsolar%2barray%26qpvt%3dISS%2bROSA%2bsolar%2barray%26FORM%3dVDRE&qpvt=ISS+ROSA+solar+array&view=detail&mid=EC96A476A78D88F84E7CEC96A476A78D88F84E7C&rvsmid=4DF232EF9F54920818AB4DF232EF9F54920818AB&FORM=VDRVRV>

DART Videos 2

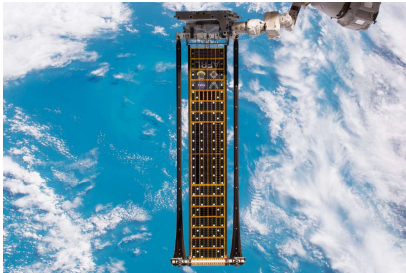


- Video "DART Behind the Scenes: Thermal Blanketing with Elisabeth Abel": https://www.youtube.com/watch?v=3_nHZvPLxPg
- Video "Behind the Scenes: Assembling the DART spacecraft (feat. Mechanical Systems Engineer Betsy Congdon)": <https://www.youtube.com/watch?v=oxKV112ut-k>
- Video "Roll-Out solar Array Technology on DART": <https://www.youtube.com/watch?v=oxKV112ut-k>
- Video "Behind the Scenes: DART High Gain Antenna Feat Matthew Bray": <https://www.youtube.com/watch?v=iTWdya4wBzw>

ROSA Flight Experiment Videos



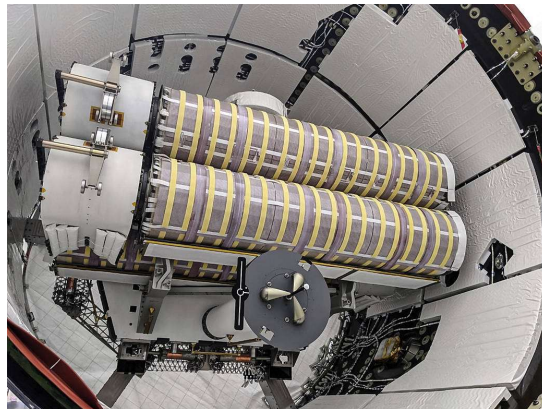
- Video of the ROSA flight experiment deploying:
<https://www.youtube.com/watch?v=1Pm4MblwRDw>
- Video of the ROSA flight experiment being jettisoned from the ISS:
<https://www.bing.com/videos/search?q=iss+rosa+flight+experiment&&view=detail&mid=7327C58D705440C860617327C58D705440C86061&&FORM=VRDGAR&ru=%2Fvideos%2Fsearch%3Fq%3Diss%2Brosa%2Bflight%2Bexperiment%26FORM%3DHDRSC3>
- <https://ntrs.nasa.gov/api/citations/20200002441/downloads/20200002441.pdf>



ISS ROSA (iROSA) Videos 1



- Video of the launch of an ISS ROSA. Shows the ISS ROSA in its stowed configuration inside the Dragon capsule's unpressurized trunk:
<https://www.bing.com/videos/search?q=ISS+ROSA+solar+array&qpv=ISS+ROSA+solar+array&view=detail&mid=3176F5F9B9A6DB37EEF43176F5F9B9A6DB37EEF4&&FORM=VRDGAR&ru=%2Fvideos%2Fsearch%3Fq%3DISS%2BROSA%2Bsolar%2Barray%26qpv%3DISS%2BROSA%2Bsolar%2Barray%26FORM%3DVDRE>



ISS ROSA (iROSA) Videos 2



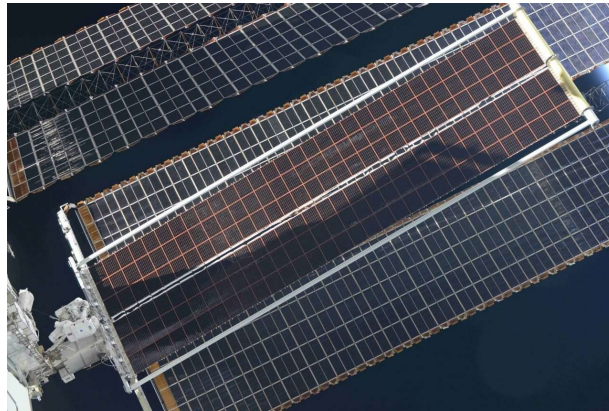
- Video on the ground deployment of an ISS ROSA solar array. No sound. Time lapse at 10x speed:
<https://www.bing.com/videos/search?q=ISS+ROSA+solar+array&qpvt=ISS+ROSA+solar+array&view=detail&mid=4DF232EF9F54920818AB4DF232EF9F54920818AB&&FORM=VRDGAR&ru=%2Fvideos%2Fsearch%3Fq%3DISS%2BROSA%2Bsolar%2Barray%26qpvt%3DISS%2BROSA%2Bsolar%2Barray%26FORM%3DVDRE>

ISS ROSA (iROSA) Videos 3



- Video of one of first ISS ROSA solar arrays being deployed on the ISS with narration:

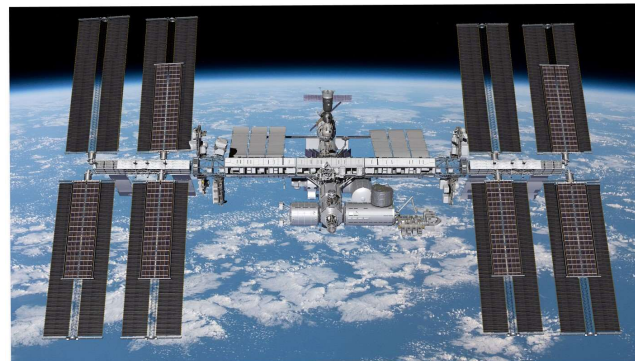
<https://www.bing.com/videos/search?q=ISS+ROSA+solar+array&qpv=ISS+ROSA+solar+array&view=detail&mid=94868F1924516566E0CE94868F1924516566E0CE&&FORM=VRDGAR&ru=%2Fvideos%2Fsearch%3Fq%3DISS%2BROSA%2Bsolar%2Barray%26qpv%3DISS%2BROSA%2Bsolar%2Barray%26FORM%3DVDRE>



ISS ROSA (iROSA) Videos 4



- Video of one of the ISS ROSA solar arrays being deployed:
<https://www.bing.com/videos/search?q=ISS+ROSA+solar+array&qpv=ISS+ROSA+solar+array&view=detail&mid=A7A4DE3A118D433AFFE8A7A4DE3A118D433AFFE8&&FORM=VRDGAR&ru=%2Fvideos%2Fsearch%3Fq%3DISS%2BROSA%2Bsolar%2Barray%26qpv%3DISS%2BROSA%2Bsolar%2Barray%26FORM%3DVIDRE>
- Artist rendition of installation of all 6 iROSA's on the ISS (8 are now expected).



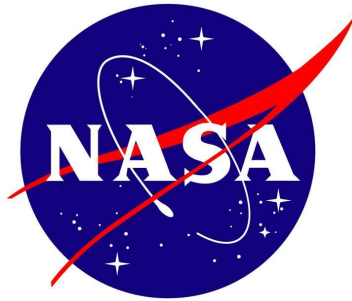
NESC L&D TDT F2F DART

25kW Class ROSA



- Video of a 25 kW Class ROSA Deployment on the ground:
<https://www.bing.com/videos/search?q=ISS+ROSA+solar+array&qpv=ISS+ROSA+solar+array&view=detail&mid=4DF232EF9F54920818AB4DF232EF9F54920818AB&&FORM=VRDGAR&ru=%2Fvideos%2Fsearch%3Fq%3DISS%2BROSA%2Bsolar%2Barray%26qpv%3DISS%2BROSA%2Bsolar%2Barray%26FORM%3DVDRE>





End