An Overview of the Distributed Space Exploration Simulation (DSES) Project

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Overview

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- HTV FCT - A Path Finding Project
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- DSES Orion/ISS Rendezvous and Docking
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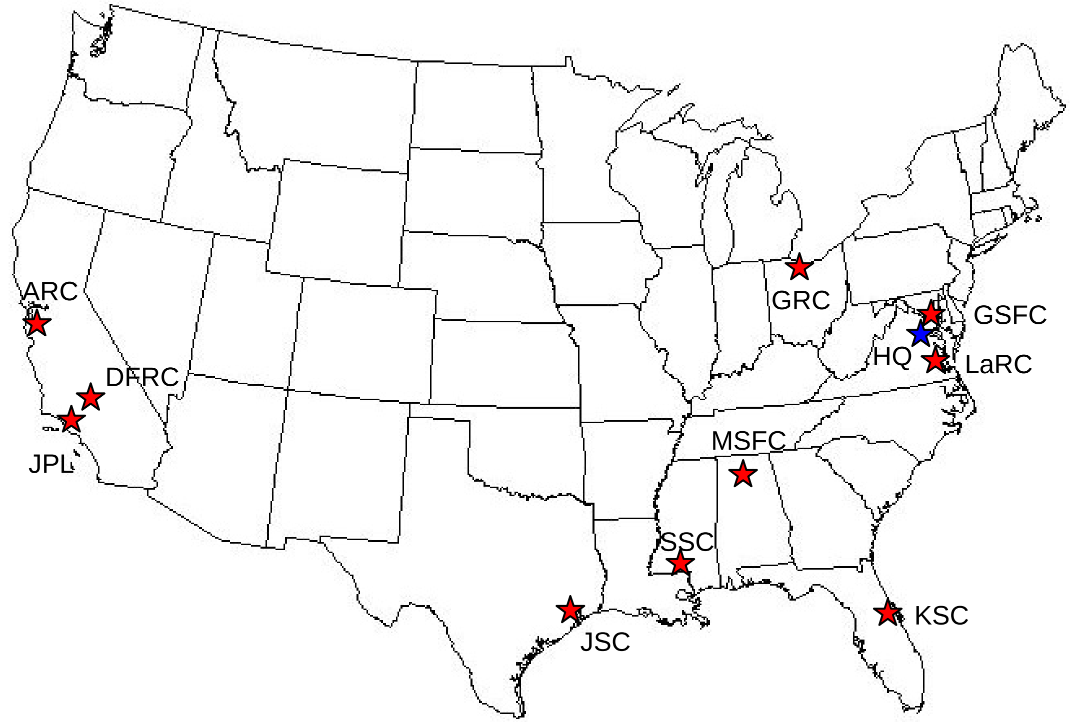
Simulation Interoperability at NASA

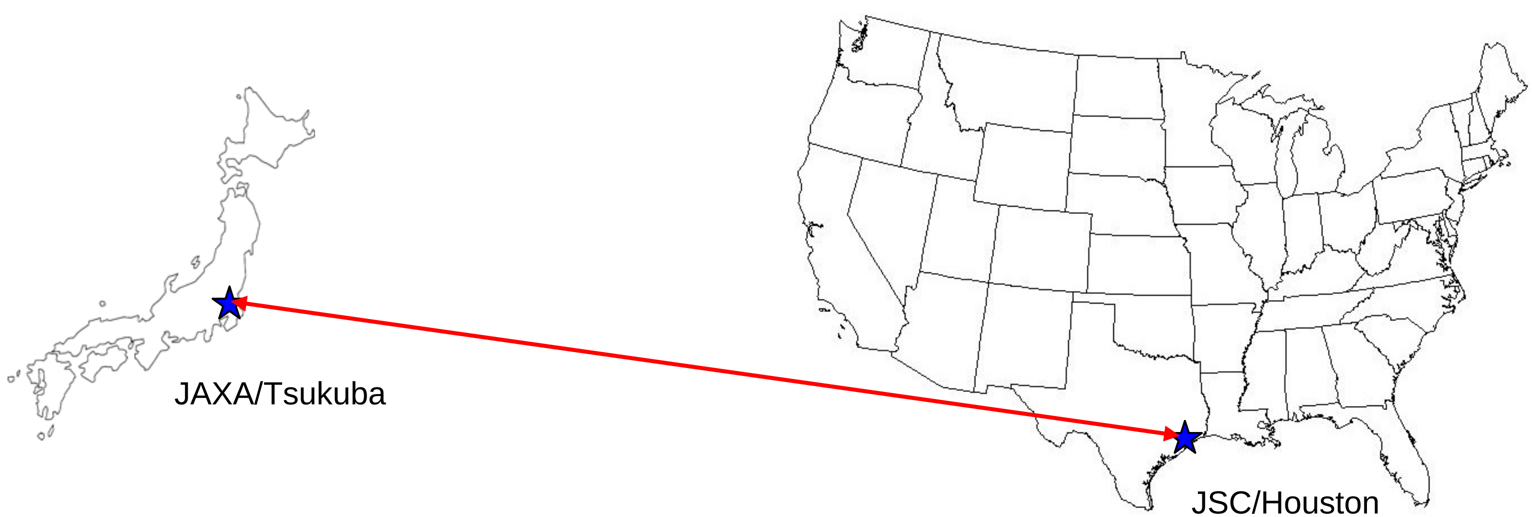
- Distributed Research Locations
  - 10 NASA Centers
  - International Partners
- Distributed Human Resources
  - Science and engineering domain expertise
  - Software engineering and programming expertise
  - Computer and network engineering expertise
- Distributed Computer Resources
  - Thousands of Computers
  - Dedicated High Speed Computer Networks
- Distributable Problems
  - Systems with well defined interfaces
  - Simulation domains with separable dynamics

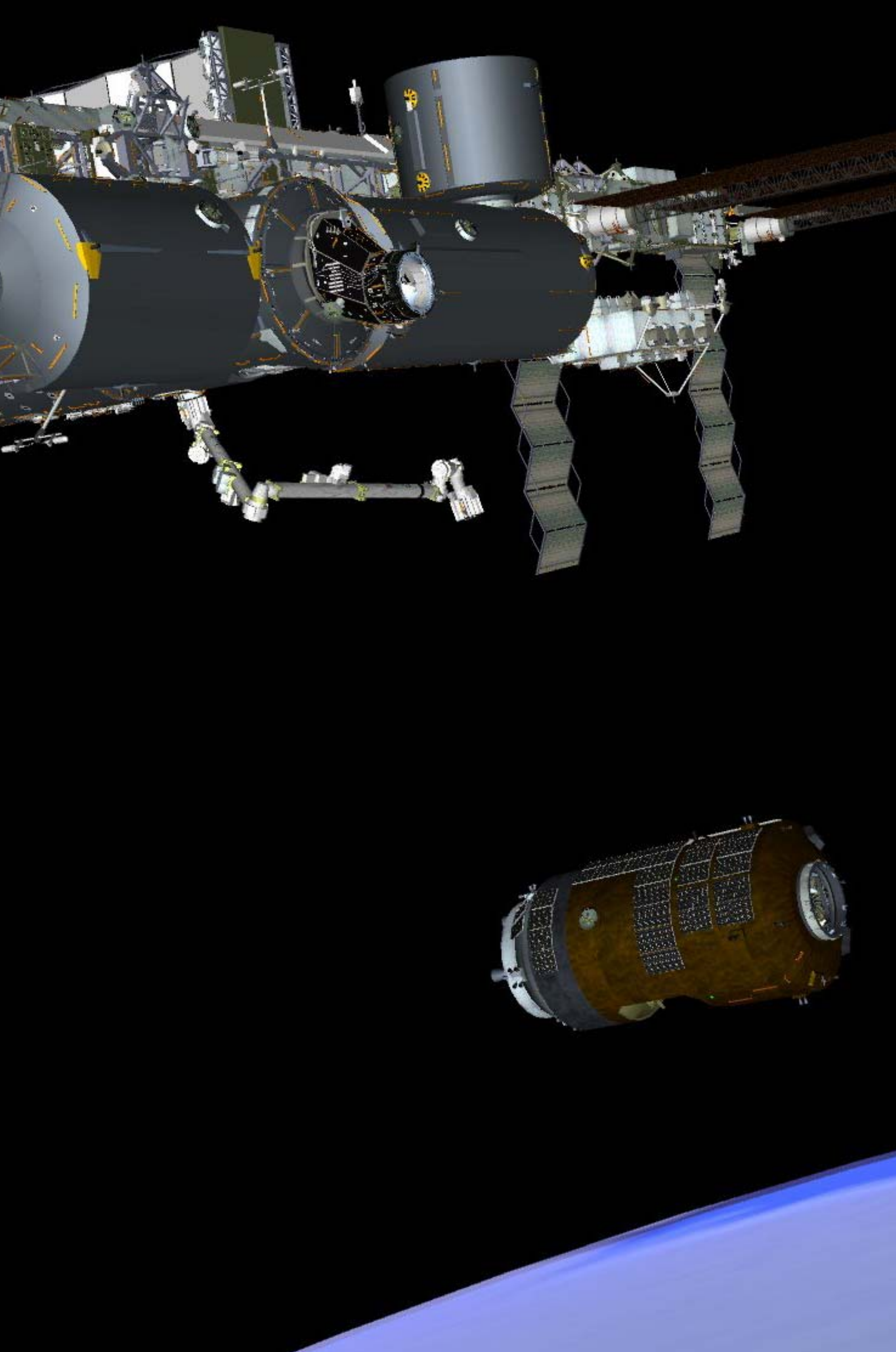


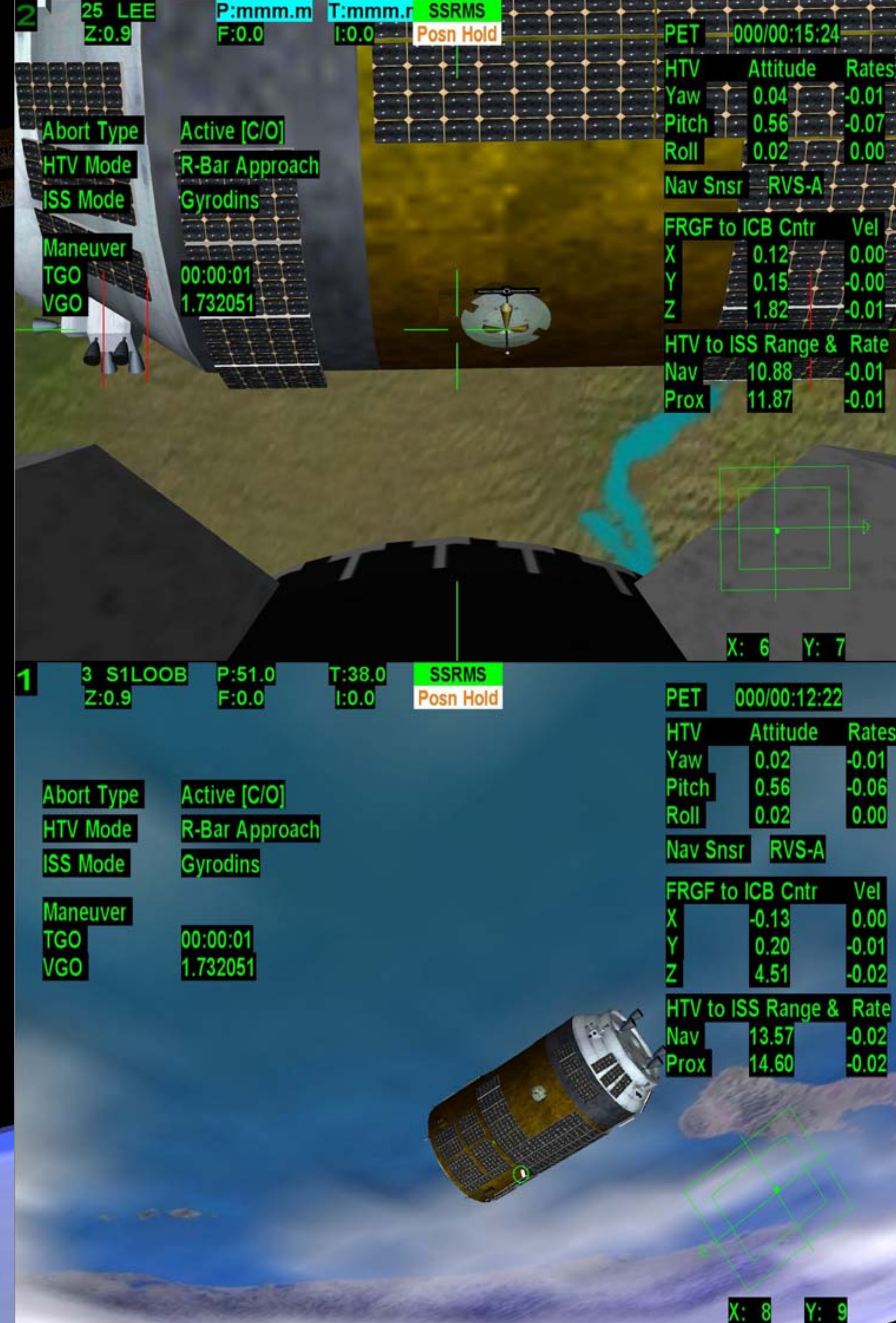
ARC - Ames Research Center	JSC - Johnson Space Center
DFRC - Dryden Flight Research Center	KSC - Kennedy Space Center
GRC - Glenn Research Center	LaRC - Langley Research Center
GSFC - Goddard Space Flight Center	MSFC - Marshall Space Flight Center
JPL - Jet Propulsion Laboratory	SSC - Stennis Space Center

HTV FCT - A Path Finding Project

- The HTV Distributed Flight Controller Trainer started in 2001
- This is a collaborative simulation project with international participation
  - This simulation consists of two principal components:
    - International Space Station (ISS) which runs in Houston, Texas, and
    - HII Transfer Vehicle (HTV) which runs in Tsukuba, Japan.
- This simulation will support flight controller procedure development and training.
- This simulation has been successfully demonstrated and is in the final phases of development. It is scheduled for deployment in late 2007 or early 2008.

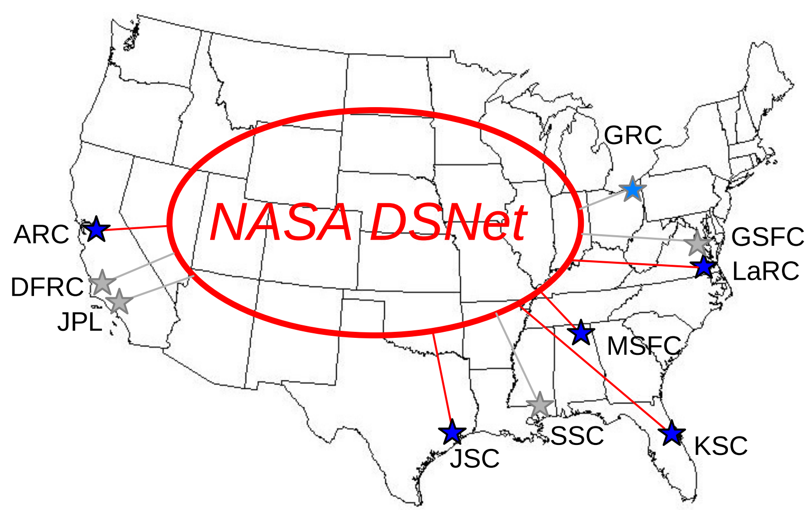





2
25 LEE
Z:0.9
P:mmm.m
F:0.0
T:mmm.r
I:0.0
SSRMS
Posn Hold
PET 000/00:15:24
HTV Attitude Rates
Yaw 0.04 -0.01
Pitch 0.56 -0.07
Roll 0.02 0.00
Nav Snsr RVS-A
FRGF to ICB Cntr Vel
X 0.12 0.00
Y 0.15 -0.00
Z 1.82 -0.01
HTV to ISS Range & Rate
Nav 10.88 -0.01
Prox 11.87 -0.01
Abort Type Active [C/O]
HTV Mode R-Bar Approach
ISS Mode Gyrodins
Maneuver
TGO 00:00:01
VGO 1.732051
X: 6 Y: 7
1
3 S1LOOB
Z:0.9
P:51.0
F:0.0
T:38.0
I:0.0
SSRMS
Posn Hold
PET 000/00:12:22
HTV Attitude Rates
Yaw 0.02 -0.01
Pitch 0.56 -0.06
Roll 0.02 0.00
Nav Snsr RVS-A
FRGF to ICB Cntr Vel
X -0.13 0.00
Y 0.20 -0.01
Z 4.51 -0.02
HTV to ISS Range & Rate
Nav 13.57 -0.02
Prox 14.60 -0.02
Abort Type Active [C/O]
HTV Mode R-Bar Approach
ISS Mode Gyrodins
Maneuver
TGO 00:00:01
VGO 1.732051
X: 8 Y: 9

The DSES Project

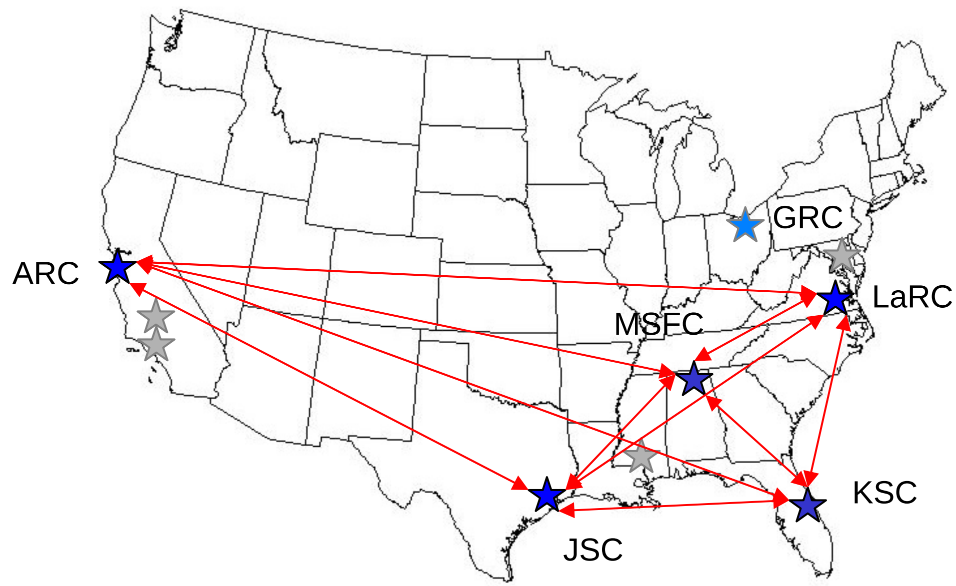
The Distributed Space Exploration Simulation (DSES) is a NASA Constellation Program (CxP), Modeling Simulation and Data Architectures (MSDA) office, multi-center product research and development project. The DSES project focuses on the development and deployment of technologies, processes and simulations which support the collaborative, interoperable and distributed simulation of complex space systems in support of NASA's Exploration Initiative.



The DSES Project

*Center Leads**

- Ames Research Center
  - Mike Blum
- Johnson Space Center
  - Edwin Z. (Zack) Crues
- *Glenn Research Center***
  - *John Lytle*
- Kennedy Space Center
  - Juan Busto
- Langley Research Center
  - Victoria Chung
- Marshall Space Flight Center
  - Mark Coffman



** - Formerly the "Coalition of the Willing"*

*** - Will join the NASA Distributed Simulation Network later in 2007*

DSES Work Areas

- Network Infrastructure
  - Develop and deploy a NASA wide network based simulation communication infrastructure (DSNet)
  - This is a prerequisite for geographically dispersed simulation interoperability
- Software Infrastructure
  - Identify/develop simulation interoperability software tools and technologies
    - These include COTS, GOTS and NASA developed solutions
    - Standardize, test and deploy these tools and technologies
  - This is a prerequisite for the effective and efficient application of interoperable simulations
- Simulation Development
  - Apply DSES network and software solutions to the development and deployment of interoperable CxP mission segment simulations
  - These simulations will provide early and relevant end-to-end program simulation capabilities

DSES Work Areas

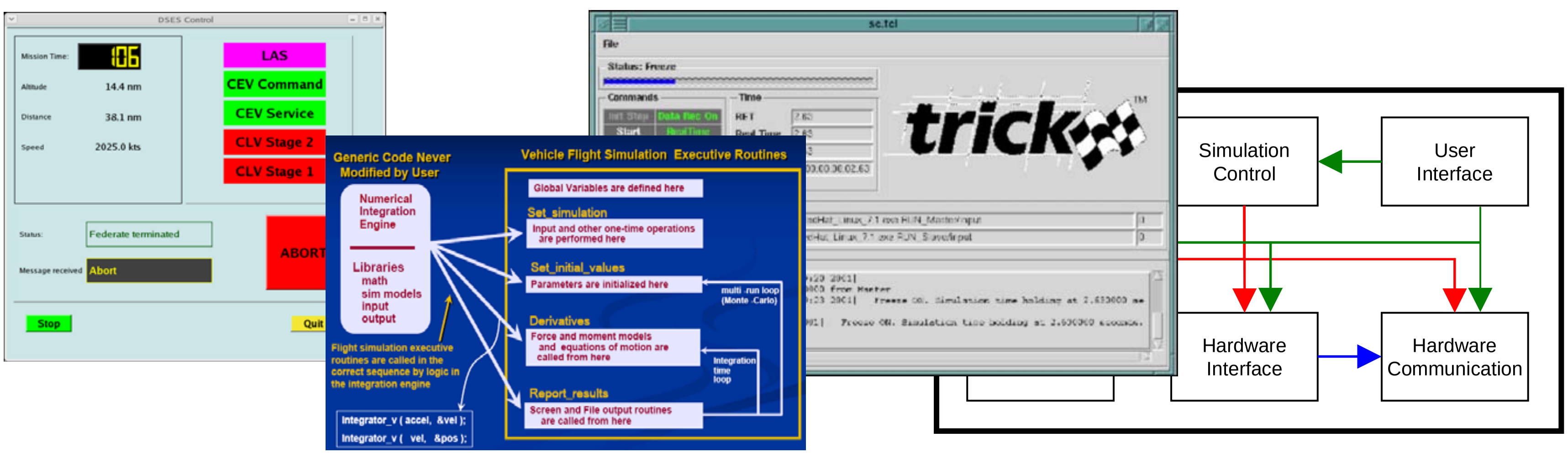
Network Infrastructure

- Develop and deploy a NASA wide network based simulation communication infrastructure (DSNet)
- Three principal FY07 Tasks:
  - Development and deployment of the NASA Distributed Simulation Network (DSNet).
  - Development and deployment of network status and performance tools for the DSNet.
  - Interoperability standards assessment (HLA, DIS/XML, TENA, XMPP, etc).

DSES Work Areas

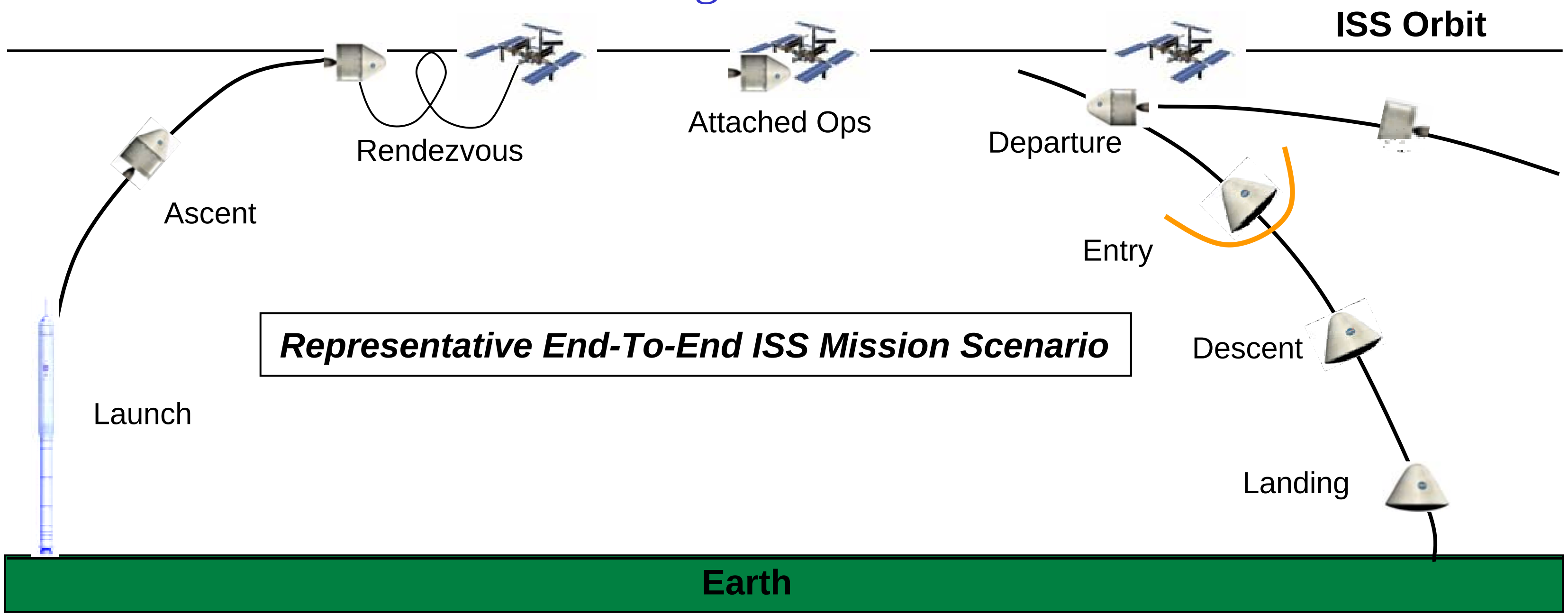
Software Infrastructure

- Identify and/or develop simulation interoperability software tools and technologies
- Three principal FY07 Tasks:
  - Development and deployment of a DSES Federation Object Model (FOM).
  - Development and dissemination of a set of standard simulation execution procedures (i.e. initialization, save and restore).
  - Development and deployment of a Trick based simulation interoperability model based on HLA.

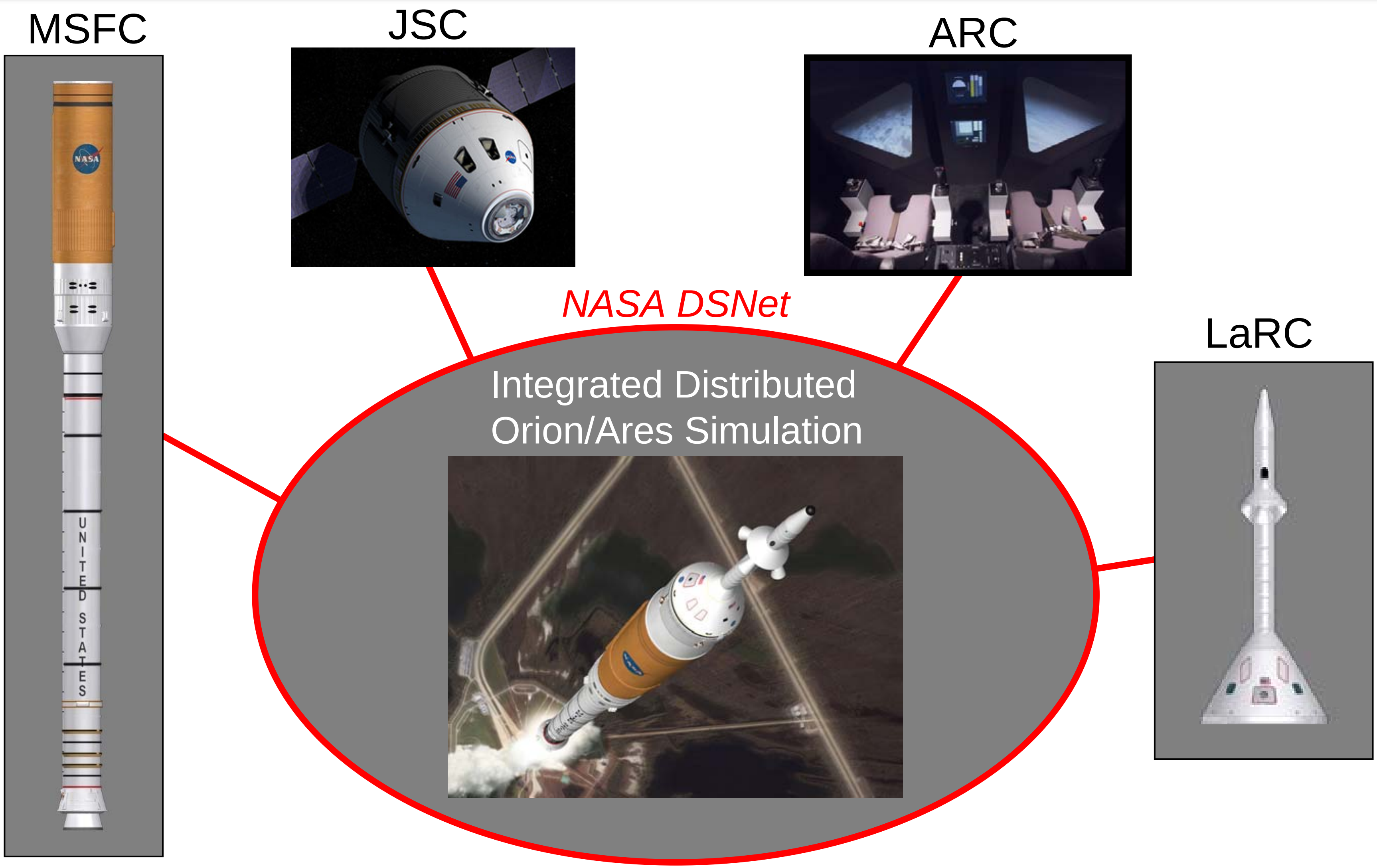


DSES Work Areas
Simulation Development

- Apply DSES network and software solutions to the development and deployment of interoperable CxP mission segment simulations
- Three principal FY07 Tasks:
  - Simulation scenario development (mission segments)
  - Simulation source identification (ANTARES, ARTEMIS, etc.)
  - End-to-end simulation integration



DSES Orion/Ares Launch and Ascent



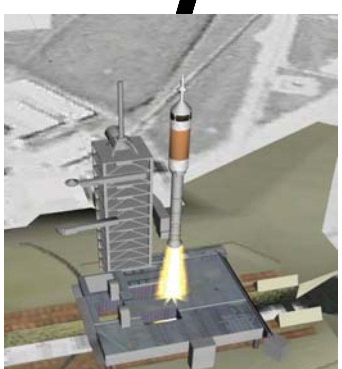
DSES Orion/Ares Launch and Ascent

It's A Hard Problem

- Need a representative problem that brings all the distributed simulation pieces together into a working system
- Chose the Orion/Ares launch problem
  - Rendezvous has been demonstrated (HTV FCT)
  - This is a HARD problem (tightly coupled)
  - This is a relevant problem
- Logical distribution of components
  - MSFC: Ares stage 1 and stage 2
  - JSC: Orion CM and SM
  - LaRC: Orion LAS
  - ARC: Crew monitoring and commanding
- Logical potential for growth
  - Ground operations (KSC)
  - Splitting out Orion SM
  - Lunar Systems
  - Mars Systems

DSES Orion/Ares Launch and Ascent

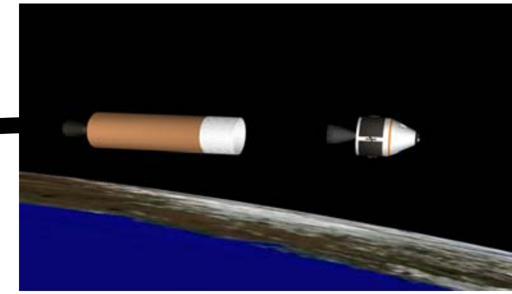
Nominal Launch Scenario



Launch

Stage 1 Separation

LAS Jettison



Stage 2 Separation

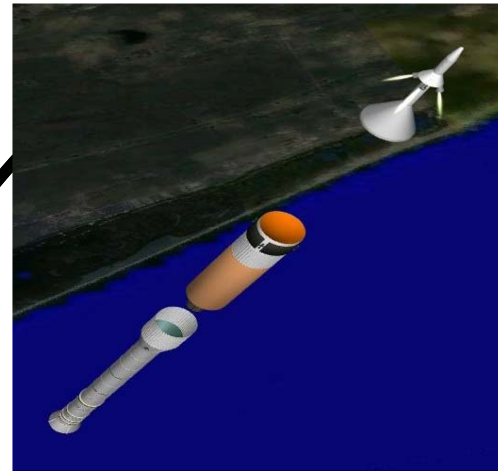
Nominal Launch Event Sequence

0.25	Stage 1 Ignition and Lift Off
130.75	Stage 1 Engine Cutoff
131.75	Stage 1 Separation
132.75	Stage 2 Ignition
161.5	LAS Jettison
592.5	Stage 2 Engine Cutoff
602.5	Stage 2 Separation
650.0	Simulation Termination

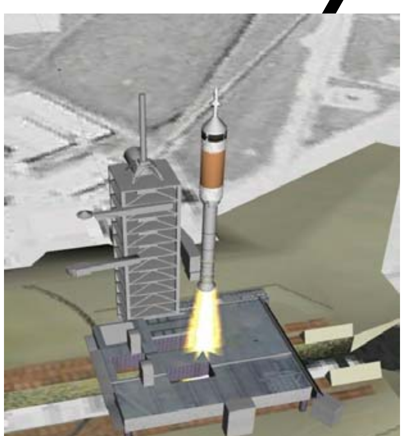
DSES Orion/Ares Launch and Ascent

Launch Abort Scenario

Abort



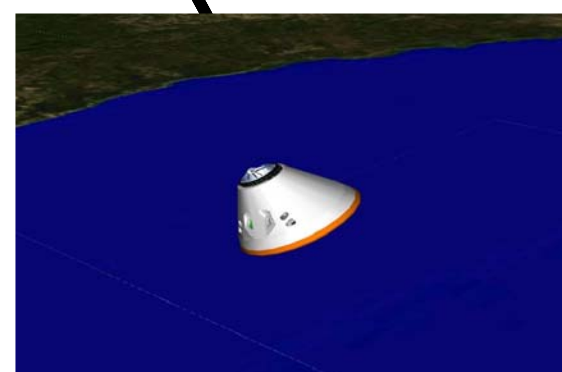
Launch



Launch Abort Sequence

0.0	Stage 1 Ignition and Liftoff
95.0	Stage 1 Engine Failure
95.25	Stage 1 Engine Cutoff
~99.0	Crew Abort Command Sent
~99.5	LAS Abort Initiated
~100.0	Stage 1 Separation
~101.0	Stage 2 Separation
~104.0	LAS Engine Burnout
~109.0	LAS Jettison
150.0	Simulation Termination

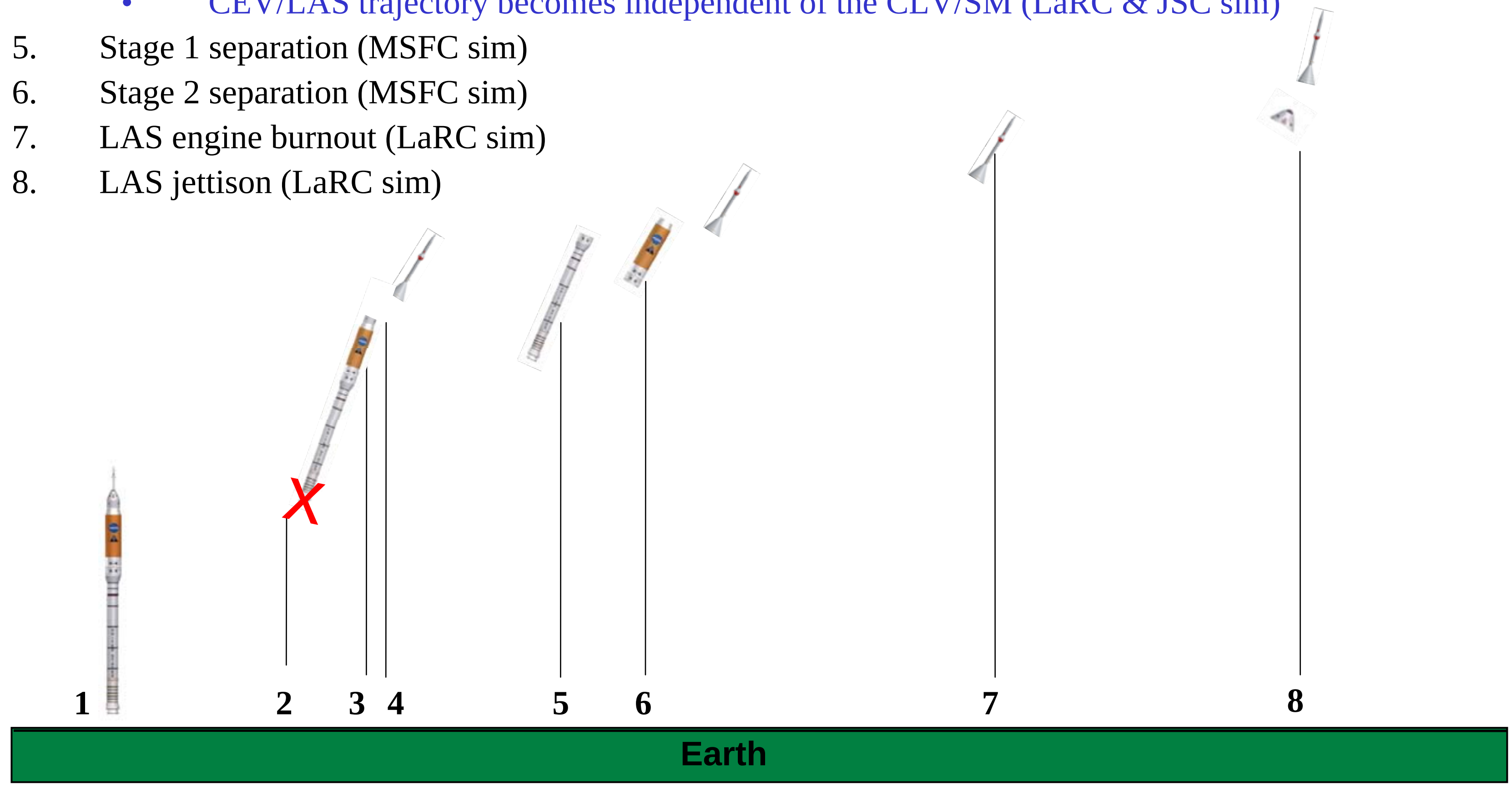
Return



DSES Orion/Ares Launch and Ascent

Abort Sequence

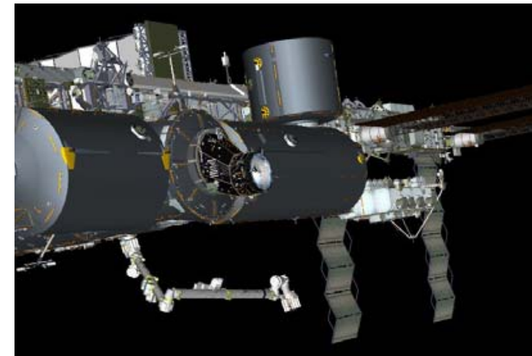
1. Launch & ascent
2. Engine failure & cutoff (MSFC sim)
3. Crew notification (ARC sim)
4. Crew initiates LAS abort (ARC sim)
   - CEV/LAS trajectory becomes independent of the CLV/SM (LaRC & JSC sim)
5. Stage 1 separation (MSFC sim)
6. Stage 2 separation (MSFC sim)
7. LAS engine burnout (LaRC sim)
8. LAS jettison (LaRC sim)



DSES Orion/ISS Rendezvous and Docking

CEV

ISS



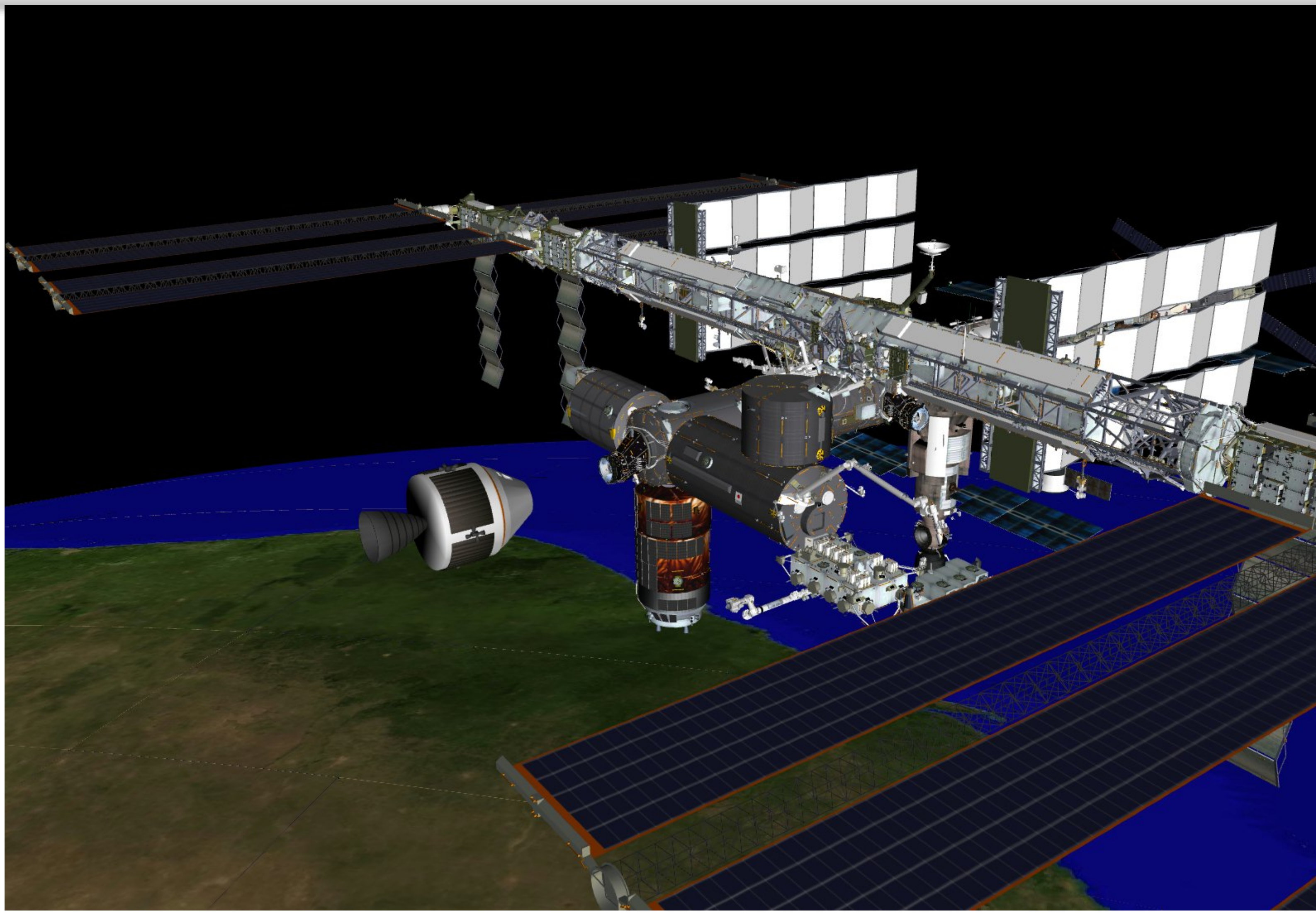
Integrated Distributed
Rendezvous and Docking Simulation

DSES Orion/ISS Rendezvous and Docking
Hardware/Human In The Loop (HITL)

- After the Launch and Ascent simulation we wanted to take the next step
- Chose the Orion/ISS rendezvous and docking problem
  - While rendezvous has been demonstrated (HTV FCT), we wanted to bring hardware and human interaction into the mix.
  - Requires real-time interfaces
  - Requires contact modeling
  - The next phase in an end-to-end Orion ISS support mission profile
- Logical distribution of components
  - Orion
    - Vehicle systems and dynamics models
    - Hand controller interface
    - Graphical views for pilot control
  - ISS
    - Vehicle systems and dynamics models
    - Could later include SSRMS

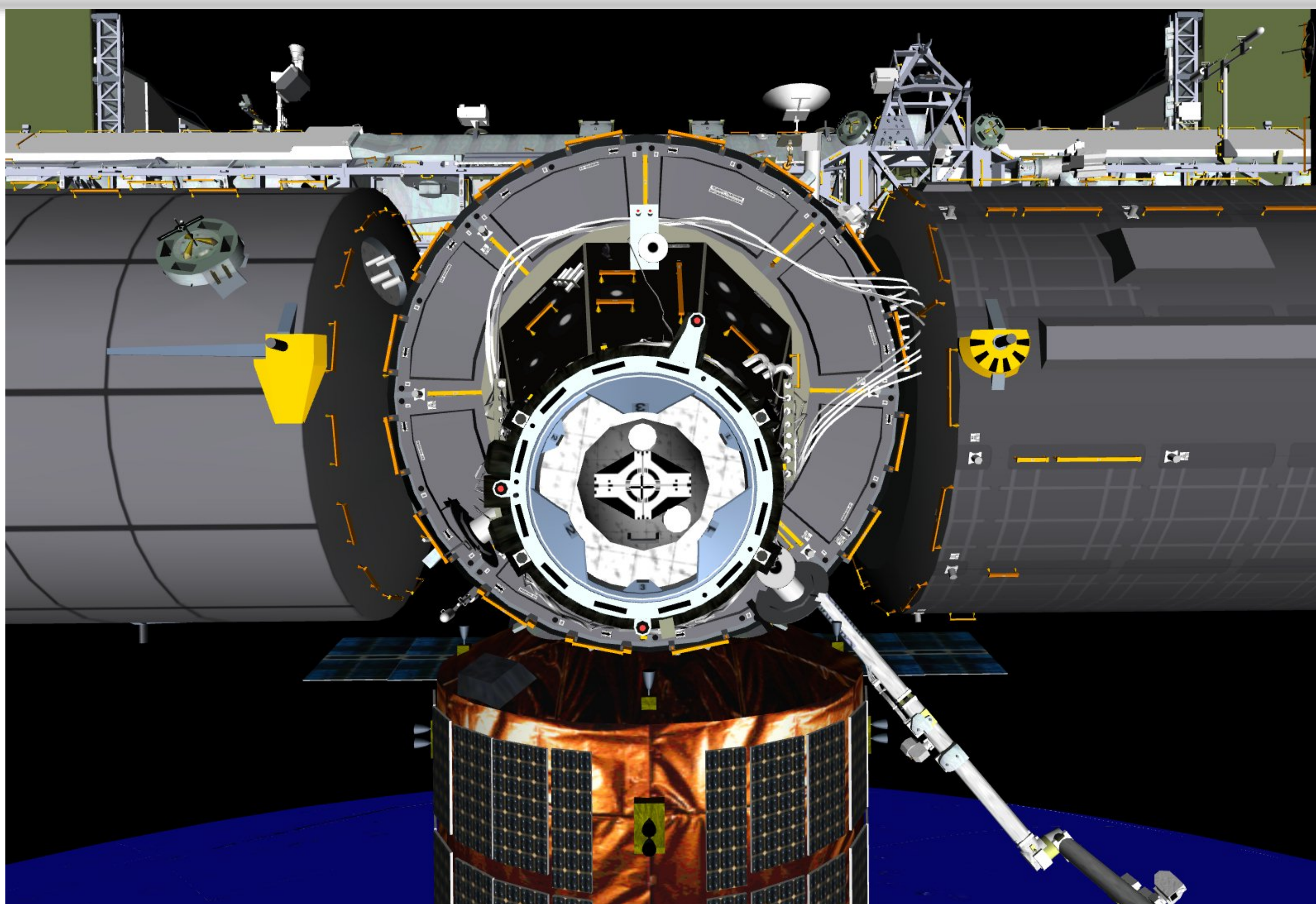
DSES Orion/ISS Rendezvous and Docking

Orion Docking to ISS



DSES Orion/ISS Rendezvous and Docking

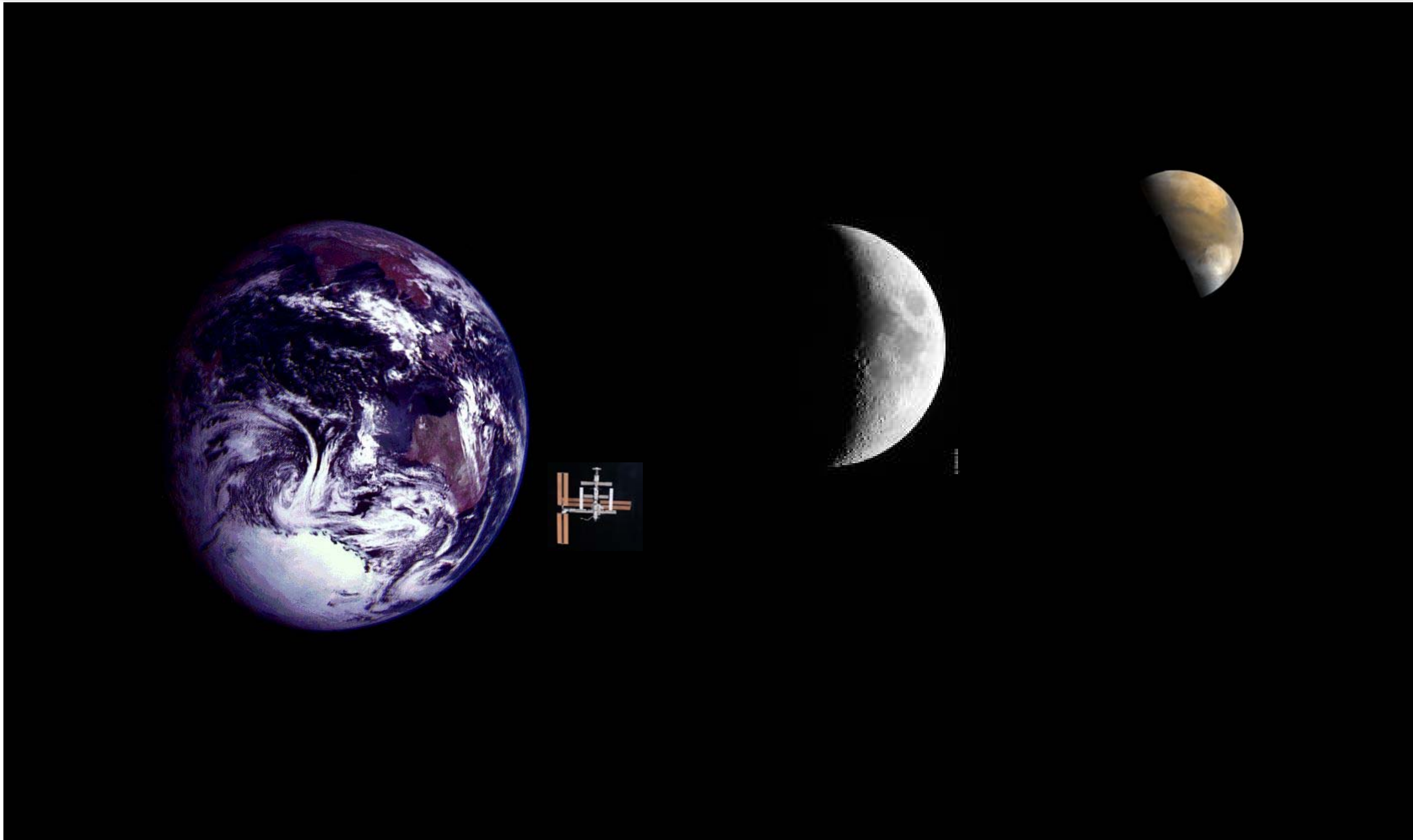
Orion Docking Bore Sight View



Closing Remarks

- Interoperability through distributed simulation
  - Establish agency wide capabilities (network and software)
  - Establish program wide standards for simulation interoperability
  - Demonstrate a framework for simulation and model interoperability/reuse
- Significance
  - Fully leverage NASA's dispersed simulation domain expertise
  - Reduce time to develop integrated mission simulation capabilities
  - Provide for more efficient and effective path to simulation VV&A
  - Increased confidence in simulation results
- Applicability
  - Already working closely with CxP T&V to establish Distributed Systems Integration Labs (DSILs)
  - Already working with CxTF to support simulation integration and reuse
  - Integrating existing project simulations
    - ARTEMIS (CLV)
    - ANTARES (CEV)
  - Looking to support more detailed CxP mission analyses

Questions?



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ABSTRACT: *This paper describes the Distributed Space Exploration Simulation (DSES) Project, a research and development collaboration between NASA centers which investigates technologies, and processes related to integrated, distributed simulation of complex space systems in support of NASA's Exploration Initiative. In particular, it describes the three major components of DSES: network infrastructure, software infrastructure and simulation development. With regard to network infrastructure, DSES is developing a Distributed Simulation Network for use by all NASA centers. With regard to software, DSES is developing software models, tools and procedures that streamline distributed simulation development and provide an interoperable infrastructure for agency-wide integrated simulation. Finally, with regard to simulation development, DSES is developing an integrated end-to-end simulation capability to support NASA development of new exploration spacecraft and missions. This paper presents the current status and plans for these three areas, including examples of specific simulations.*

1. Introduction

The NASA Distributed Space Exploration Simulation (DSES) Project is developing technologies and processes related to collaborative simulation of complex space systems.

The traditional approach to the space vehicle simulation is through disjoint collections of individual simulations. Each simulation usually focuses on a specific domain aspect of a space vehicle and is developed, maintained and executed at the facility having the particular domain expertise. While this provides high fidelity modeling in particular areas, other domain areas are usually modeled to a lower fidelity. When higher fidelity simulation across the whole system is needed, larger and more complex simulations are built. Often, these bigger simulations re-implement existing models in a different simulation architecture.

However, a new approach to building large scale simulation is emerging. This is the area of *distributed simulation*. In this case, the simulation is actually a set of distributed, interacting smaller simulations. This approach has a number of benefits. For instance, organizations with specialized domain expertise can contribute to the aggregate simulation thus combining their individual expertise into a larger body. Another benefit is the ability to restrict access to or hide the details of proprietary technologies or algorithms while permitting their use in the overall simulation. Yet another benefit is the ability to distribute the cost of development across multiple organizations and utilize the shared computer resources of those organizations.

One of the leading distributed simulation technologies in use today is the High Level Architecture (HLA) which was originally developed and deployed by the U.S. Department of Defense (DoD) Defense Modeling and Simulation Office (DMSO). This is an evolution of previous DoD distributed simulation technologies and has now been adopted in a modified form as an international standard by the Institute of Electrical and Electronics Engineers (IEEE) as the IEEE 1516 HLA standard. [1]-[4] HLA is a key element of the current DSES software infrastructure.

The sections below provide an overview of the DSES project and the infrastructure and simulations currently being studied.

2. Project Overview

The principal objective of the DSES project is to investigate distributed simulation in general (initially using HLA) and in particular to build large scale integrated space vehicle simulations in support of the Constellation Program (CxP). The Constellation Program is responsible for implementing the vision of the Exploration Systems Mission Directorate (ESMD), which leads NASA's new exploration initiatives. DSES involves scientists and engineers from all 10 of NASA's research and flight facilities.

Previous work. One precursor to the DSES project is the DIstributed Simulation (DIS) project, which is a distributed simulation for use in flight procedures development and training of the HII-A Transfer Vehicle (HTV) and its operations in proximity of the International Space Station (ISS). This simulation is referred to as the HTV Flight Controller Trainer (FCT) simulation. It is a collaborative effort between the Japanese Aerospace eXploration Agency (JAXA) and the NASA Johnson Space Center (JSC) Mission Operations Directorate [5][6]. In this simulation, HTV components run at JAXA facilities in Tsukuba, Japan and ISS components run at JSC in Houston, Texas. A graphic scene generated from this simulation is shown in Figure 1.

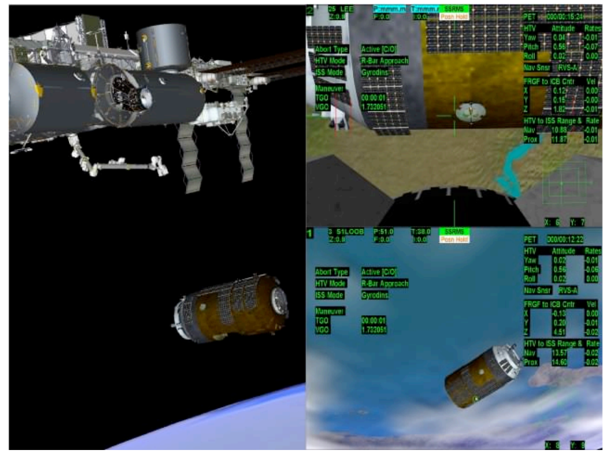

Figure 1: The HTV FCT Simulation

Much of the knowledge and technologies used in the HTV FCT have been directly applied to the DSES project.

Early DSES. Initially, the DSES project was referred to as a "coalition of the willing" in the sense that small groups of NASA scientists and engineers with similar interests and very little funding met on a regular basis to exchange information and ideas on new approaches to simulation. These groups located at JSC, NASA Ames Research Center (ARC) and NASA Langley Research Center (LaRC) configured a small informal network of computers and began testing out some simple distributed simulations. As the DSES work progressed, interest began to spread to other centers. Another interested group at NASA Marshall Space Flight Center (MSFC) soon joined the growing DSES team. Currently, a group at NASA Kennedy Space Center (KSC) is joining in on the DSES work. This will bring the count to five NASA centers with plans to extend to all NASA centers in the coming years.

Early DSES work focused on three areas: *Infrastructure*, *Expertise* and *Product*. The infrastructure work involved building up the computer, network and software systems required to support a distributed simulation capability. The process of developing and using distributed simulation was the most effective way to build expertise. Finally, the team began creating a DSES "product" by building up distributed tools and simulations used for the analysis, planning, construction, development and operation of future space exploration systems.

To build up these areas, the DSES project adopted an open-ended development plan based on iterative development. The product of each iteration was a working distributed simulation of a space vehicle. Every iteration built up one or more of the three areas, improving NASA's overall capabilities to design, develop and deploy complex distributed simulations of space exploration systems.

Orion/Ares. In September of 2006, the DSES project successfully demonstrated a distributed version of the Orion/Ares launch vehicle. (See Figure 2.)

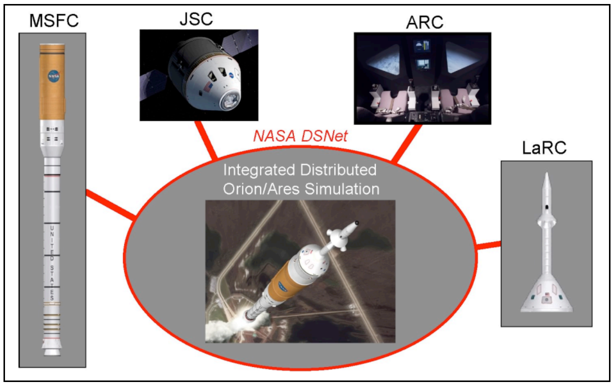

Figure 2: Orion/Ares Launch Simulation

This simulation is composed of four federates[1] each providing functionality for important subsystems in the vehicle stack. The Ares launch vehicle or Crew Launch Vehicle (CLV) federate is an MSFC simulation. The Orion spacecraft or Crew Exploration Vehicle (CEV) federate is a JSC simulation. The Orion Launch Abort Systems (LAS) federate is a LaRC simulation. The final federate is the crew interaction simulation which runs at ARC. All these federates are run in a federation of simulations to demonstrate an integrated and distributed simulation of the Orion/Ares vehicle from launch, through LAS jettison, through stage 2 separation and on to orbit.

Next steps. As the DSES project now moves out of its early formative and development phases, the project will transition from a mostly research and development project into a primarily product development project. In that regard, the DSES project will again focus on three areas; however, this time they are: Network Infrastructure, Software Infrastructure and Simulation Development.

3. Network Infrastructure

While most simulations require an infrastructure of computers and software, distributed simulations also rely heavily on a network. As a result, the DSES project will focus on building up NASA's network infrastructure to support distributed simulation.

[1] Participants in an HLA system are called *federates*.

3.1 NASA Distributed Simulation Network (DSNet)

The DSES network infrastructure is currently based on an interconnection of center-specific local area networks through the NASA Integrated Services Network (NISN). This, with a combination of externally accessible IP addresses and access allocations through the facility network firewalls, forms the NASA Distributed Simulation Network (DSNet). While the current network has limited levels of service guarantees, the determination of the form and necessity of network guarantees is an area of DSES investigation.

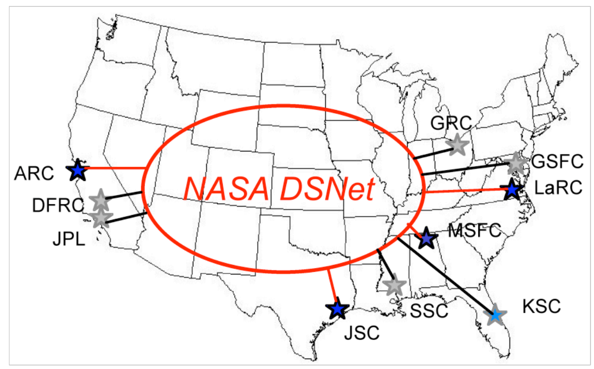

Figure 3: Distributed Simulation Network

Currently, there are 5 NASA centers connected through the DSNet: ARC, JSC, KSC, LaRC and MSFC. There are plans to connect the remaining 5 NASA centers as project participation expands.

While the DSNet was originally intended for basic connectivity to DSES distributed simulations, its scope has expanded to include additional Constellation projects like the Command, Control, Communication and Information (C3I) Constellation of Labs (CofL) and the Distributed Systems Integration Labs (DSILs).

There are currently plans for the DSNet to provide two categories of service: *Facility* and *Commodity*. The Facility category of service will provide Constellation facilities at various NASA centers a lab facility-to-facility high bandwidth, high reliability connectivity with specific service level guarantees. The Commodity category of service will provide general distributed simulation connectivity between any computer at any facility at any time.

3.2 Network Status and Performance Tools

Unfortunately, it is not enough to just establish connectivity between computers at the geographically dispersed NASA centers. It is also important to have insight into both the current status and performance of the network connections. This is being accomplished through the creation of a collection of DSNet status and performance tools.

Packet loss. HLA messaging and Trick simulations were established between JSC and AMES by early 2006. Subsequently, a backup network path through the open Internet was established. The freely available network test software package, iperf, was used to measure network statistics, and showed an initial directional packet loss of 2% on one of the connection links, but more than 30% going the other direction! The DSES team worked with NISN, feeding them performance measurements while NISN tried different solutions. The performance did improve, with packet loss dropping to less than 2% across all links.

Firewall rules. At each participating center, the typical template for network architecture resulted in computers behind firewalls whose rules required specific modifications and additions. These actions were necessary to allow the DSES computers they protected to establish sessions and to allow 2-way packet exchanges with all other external DSES nodes.

This proved to be the most time consuming and error-prone step. As LaRC and MSFC joined, it was clear that there was a definite risk that there might be errors introduced by someone at one of the new or established DSES centers. These errors typically result in packets blocked at some firewall, in effect breaking an existing previously proven connection to other nodes on the network. This did happen, resulting in the DSES practice of banning the attempted implementation of firewall rule changes in the weeks leading up to important simulations. Fortunately, backup hosts were able to perform when primary hosts suffered broken connections. ARC work in 2007 involves setup of a more forward end node with fewer firewall rules to contend with, operating initially in parallel with the default original architecture, in order to test proxy server concepts with JSC, latency, and reliability issues.

Automated monitoring. Based on early experience, DSES now has automated tools for testing network connectivity and performance. This automation saves roughly 2 hours per week of manual effort. By the time of the DSES demo in September 2006, browser based tools had been written by ARC and MSFC to automate the collection and presentation (including charts and plots) of jitter and packet loss information on all 6 links between the 4 NASA centers.

Current DSES work includes efforts to build better test tools. The work focuses on more accurate testing, measurement of more parameters, and more intelligent automation. In 2006, the network testing across all links was hourly and consisted of a single procedure executing all the tests. In 2007, the network health tools are consuming less bandwidth, and becoming more scalable by running mostly isolated link tests and by using more packets during certain times (for example, the hours immediately before an integrated simulation).

4. Software Infrastructure

DSES is a collaborative effort between NASA centers. The project capitalizes on expertise and simulation capabilities that already exist in the agency. The DSES software infrastructure consists of a *common framework* that allows *existing simulation tools* at NASA centers to cooperate in a single distributed simulation. The participating centers use the framework to build their contributions to the overall simulation using their in-house simulation tools. The framework provides the "glue" that integrates the various contributions, providing interfaces for execution of the simulation, data exchange, and distributed time management.

4.1 DSES, HLA and the Federation Object Model (FOM)

Currently the DSES framework is based on IEEE 1516 (HLA). Other technologies are being studied, but the current DSES simulation involves distributed *HLA federates* joining together into a single distributed *HLA federation*. The federates are built using the in-house simulations tools at each NASA center and integrated using HLA.

In HLA, all the federates must agree on a single *federation object model* (FOM), which is a common data dictionary defining the data to be shared. The DSES FOM currently includes space vehicle state such as position, velocity and acceleration. It also includes of event-like such as vehicle command and status information. As the simulations mature, the DSES FOM will grow to include additional states and events. Ultimately, it will have to be compatible with and captured in the coordinated and standardized Constellation Project knowledge base called the NASA Exploration Information Ontology Model (NExIOM).

4.2 NASA Simulation Software

One of the DSES accomplishments has been the development of a framework that allows the integration of HLA into the simulation tools used by the teams at the various NASA centers. Teams at ARC, JSC, LaRC and MSFC integrated their simulation tools into DSES. These tools are summarized below.

Ames Research Center. ARC uses an in-house real time operating system known as *microTau,* which was developed for high fidelity vertical motion simulation, including the Shuttle and lunar landings. The environment allows relatively fast development and deployment of new models and the addition of new computing hardware and force feedback inceptors. Simulation parameters can be changed on the fly. The overall system involves local Ethernet, SCRAMNET, and XIO memory sharing tools, and interfaces to other protocols and media.

ARC also has an extensive HLA environment bridging three facilities, adding different motion simulators, and a 360 degree panoramic control-tower-style visualization and control center to any distributed simulation. Ongoing work includes the addition, to the DSES network, of the Integrated Vehicle Health System (IVHS) and Advanced Diagnostics and Prognostics Testbed (ADAPT) Laboratories.

Using their expertise in building simulations in these systems, ARC built the crew in the loop abort initiation portion of the DSES simulation.

Johnson Space Center. Over the years, JSC has been moving to a common simulation development tool, *Trick* [7]-[9]. Trick automates many of the tedious processes in constructing simulations and provides a number of generalized simulation capabilities. In addition, JSC has been assembling a *collection of common models*. These models, while hosted in the Trick environment, are not necessarily Trick dependent. This goal is to develop a suite of space systems models that can be shared across projects and facilities.

JSC DSES simulations are built using Trick and this collection of common models. One of these is the *Advanced NASA Technology Architecture for Exploration Studies (ANTARES)*, a multi-purpose simulation supporting the Crew Exploration Vehicle (CEV) Guidance Navigation and Control (GN&C) team. ANTARES will form the core of the JSC contribution to DSES on-orbit simulations, such as CEV/ISS rendezvous and docking.

Langley Research Center. At LaRC, the Flight Simulation and Software Branch has been providing flight simulation products and services since the 1950s. Their current simulation framework is the Langley Standard Real-Time Simulation in C++ *(LaSRS++)* framework [10]-[19]. While originally developed to support aircraft simulation, the framework can be used to simulate many kinds of systems.

LaSRS++ consists of a suite of software libraries that can be shared among developers, projects, and facilities, and it provides services required to run simulations, permitting developers to focus only on vehicle model development. The framework includes various world models such as Earth, Lunar, and Mars atmospheres. It supports real-time human-in-the-loop, hardware-in-the-loop, and parametric simulation and analyses. It supports multiple simulation aspects such as Guidance, Navigation, and Controls, vehicle dynamics and behavior, trajectory analysis, vehicle performance assessment, crew displays, and flight deck avionics and layout for part task or end-to-end full mission simulation.

The LaRC DSES simulation is derived from the LaSRS++ generic spacecraft model.

Marshall Space Flight Center. Over the years MSFC has developed the Marshall Aerospace Vehicle Representation in C II (MAVERIC-II) program [20]. This program is designed to more rapidly create flight simulations for spacecraft and launch vehicles. It can be used for all steps of vehicle development — from concept design to actual flight of a finished vehicle. MAVERIC-II simulations can provide detailed predictions of how vehicle designs will actually perform before the craft is built and flown.

MAVERIC contains generic models for the propulsion system, the reaction control system, vehicle aerodynamics, the atmosphere (GRAM, US62, US76), mass properties, winds, and it has algorithms that emulate flight software for guidance and navigation systems. The system can be run in both 3-DOF and 6-DOF simulation modes. 3-DOF mode amounts to perfect attitude control and is typically used when design additions or changes to the guidance algorithms are being evaluated.

In the DSES federation configuration, MAVERIC is executed in full 6-DOF mode.

4.3 Trick HLA Classes

Each of the simulations tools discussed above required slight modifications in order to integrate with the DSES framework. The details of those modifications are not discussed here. However, one objective of the DSES project is to make these kinds of customizations less necessary by developing software that allows arbitrary Trick based simulations to participate in a

DSES simulation without having to explicitly integrate HLA logic. The objective of this work is to understand how to minimize the effort involved in customizing the various simulations tools.

JSC is creating a generalized set of HLA classes that can be incorporated into a Trick based simulation. These classes take advantage of some of Trick's generalized input/output and variable access capabilities to provide a model that can be included into almost any Trick based simulation to allow it to join into almost any DSES Federation. The mapping of the FOM to Trick data structures is handled transparently at runtime, making integration of a simulation into an HLA federation substantially easier for developers.

These Trick/HLA classes will be made available to all Constellation simulation developers who are developing Trick based simulations.

5. Simulation Development

While the DSES project is extremely interested in the technological aspects of distributed simulation (i.e., network and software infrastructure), the main objective is to develop products (models, simulations and analysis) with meaningful scientific and engineering application to NASA's space exploration initiatives. To accomplish this goal, the DSES project is using an evolutionary development process. In this process the various models and systems required for a working distributed simulation of a space exploration vehicle are developed in phases. The early phases have concentrated on technology demonstrations and simulation architecture development. The next phases will demonstrate modeling capabilities, data exchange, model exchange and coordinated execution. The final phases will demonstrate integrated system execution and analysis products.

5.1 DSES Initialization and Startup Process

One of the challenges faced by the DSES team was how best to coordinate the initialization and startup of the collection of federates in any given DSES Federation. The DSES team determined the need for a generic initialization sequence that can be used to create a federate that can:

1. Properly initialize all HLA objects, object instances, interactions, and time management
2. Check for the presence of all federates
3. Coordinate startup with other federates
4. Robustly initialize and share initial object instance data with other federates.

To address these requirements, the following initialization process is used in all DSES federates:

1. Create the federation
2. Publish and subscribe
3. Create object instances
4. Confirm all federates are joined
5. Achieve "initialize" Synchronization Point
6. Update object instance(s) with initial data
7. Wait for object instance reflections
8. Set up time management
9. Achieve "startup" Synchronization Point
10. Start execution

The details of the DSES initialization and startup process are beyond the scope of this paper and are covered in a companion paper [21].

5.2 Dynamics Comparison

One significant requirement for a distributed or collaborative simulation is that the fidelity of the component simulations be compatible.

Initially, it may seem sufficient to have each DSES participant build a 6 Degree of Freedom (DOF) space based simulation, agree on initial conditions, execute the simulation and compare state and environment variable histories. However, the likelihood of getting exact or even numerically equivalent matches between these simulations rapidly approaches zero given the diversity of model implementations and simulation environments. DSES follows a multi-step testing process in order to reduce the likelihood of these kinds of inconsistencies. The process involves a progressive increase in modeling complexity and for the systematic identification and categorization of the sources and sizes of comparative modeling differences.

The test plan for the DSES dynamics comparison tests consists of following ten principal "unit" comparison test cases and a final fully integrated comparison test case:

- Test Case 1: Earth Modeling Parameters
- Test Case 2: Keplerian Propagation
- Test Case 3: Gravity Modeling
- Test Case 4: Planetary Ephemeris
- Test Case 5: Atmospheric Modeling
- Test Case 6: External Force Affects
- Test Case 7: Combined Translational Test
- Test Case 8: Torque Free Rotation
- Test Case 9: Torque Driven Rotation

- Test Case 10: Gravity Gradient Torque
- Full Test: Integrated 6 DOF Test

Each test case consists of one or more run scenarios. The test cases and their associated scenarios are designed to test specific contributions to the dynamic propagation of a 6 DOF simulated space vehicle.

Like the DSES initialization and startup process, the details of the dynamics comparison process are beyond the scope of this paper and will be covered in a companion paper.

5.3 End-to-End Simulation Capability

The ultimate products for DSES are simulations and the analysis and training that they can provide. Specifically, DSES will be providing end end-to-end simulation capability for all the mission segments in the Constellation program. This includes simulations that range from ground operations, to launch, to orbit, to interplanetary transit, to planetary operations, to Earth return and finally to entry, descent and landing.

Vehicle Elements. In order for DSES to provide simulation support for all Constellation mission scenarios, it will have to provide simulation capabilities for all the elements of the Constellation vehicles listed below:

International Space Station (ISS)
Orion - Crew Module (CM)
Orion - Service Module (SM)
Orion - Launch Abort System (LAS)
Ares I- First Stage
Ares I- Upper Stage
Ares V - Core Stage
Ares V - Solid Rocket Boosters (SRBs)
Earth Departure Stage (EDS)
Lunar Surface Access Module (LSAM)

Currently, DSES has vehicle models for the ISS, CM, SM, LAS, Ares I First Stage and Ares I Upper stage. These vehicles vary in their level of fidelity and are continually being modified to track vehicle development and enhanced with improving levels of fidelity. The LSAM, EDS and Ares V elements are currently in development.

Mission Scenarios. Current FY07 development plans for DSES include the following four principal mission segments:

1. Ground Operations
2. Launch and Ascent
3. Orbital Rendezvous and Proximity Operations
4. Entry Descent and Landing.

This will be expanded to include all other mission segments as the Constellation program advances.

The *Ground Operations* mission segment involves the ground processing of the Orion/Ares launch vehicle in preparation for and up to launch. This capability is not currently integrated into DSES but is included in the FY07 development and integration plans.

The *Launch and Ascent* segment involves the launch, liftoff, and ascent to obit of the combined Orion/Ares launch system. This includes launch countdown and interactions with the Launch Control Center (LCC) as well as the interactions with the Mission Control Center (MCC) and both nominal and contingency launch system ascents. See Figure 4 for a DSES generated view of the Orion/Ares launch vehicle lifting off.

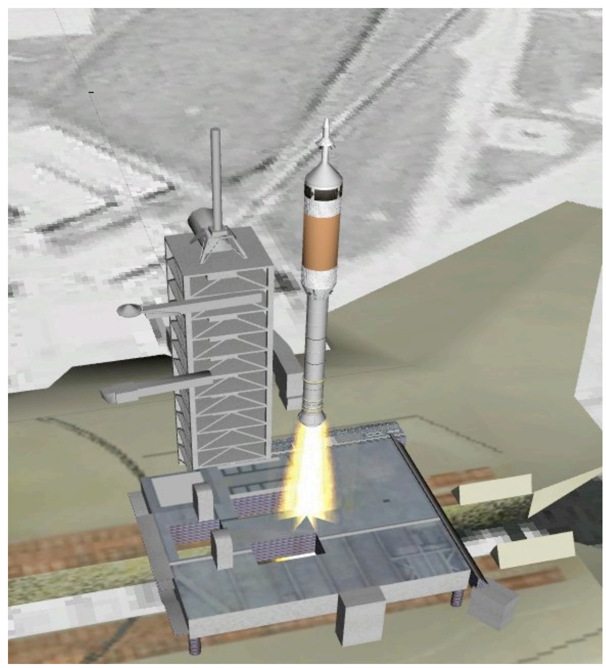

Figure 4: DSES Launch and Ascent Simulation

One of the principal early missions for the Orion spacecraft is to service the ISS. Once Orion is in orbit it will rendezvous with the ISS and then dock. This requires simulation support for rendezvous with and proximity operations around the ISS. See Figures 5 and 6 for a DSES generated view of the Orion spacecraft docking with the ISS.

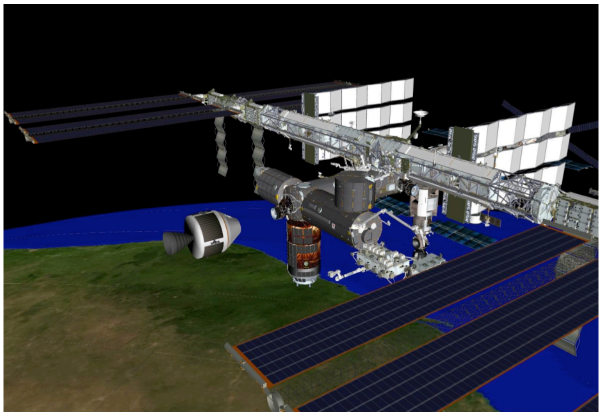

Figure 5: Orion Docking to ISS

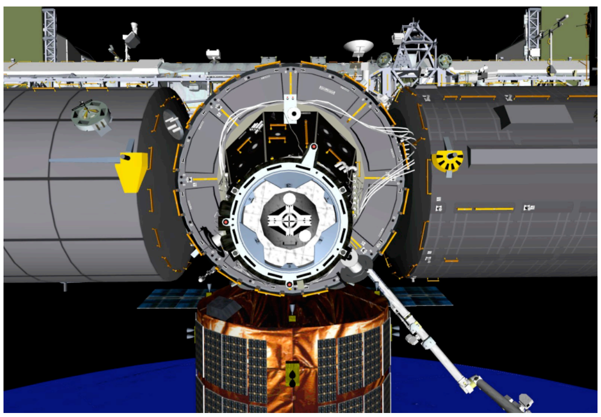

Figure 6: Docking Boresight View

Once the Orion spacecraft has completed its mission at the ISS, it will separate from the ISS and return to Earth. This requires an entry, descent and landing capability. This capability is not currently integrated into DSES but is included in the FY07 development and integration plans.

6. Concluding Remarks

The DSES project is a collaborative project that currently includes 5 NASA centers: ARC, JSC, KSC, LaRC and MSFC. DSES utilizes technical domain expertise and resources from each of these centers to effectively support the Constellation Program with its simulation needs. In the process, DSES provides a unifying approach to simulation across NASA and makes efficient use of NASA's simulation development resources.

The Distributed Space Exploration Simulation (DSES) will provide an end-to-end simulation capability for the Constellation Program. For FY07, this includes all mission segments for the Orion spacecraft and its service missions to the International Space Station.

As the Constellation Program advances, new mission segments will be added. This will include missions to return humans to the Moon. (See Figure 7 for a DSES generated view of the Orion/LSAM in orbit about the Moon.) Ultimately, the Constellation Program will extend human presence beyond the local Earth/Moon system to the planet Mars. As these and other mission segments evolve, DSES will evolve to provide the high fidelity mission simulation needs.

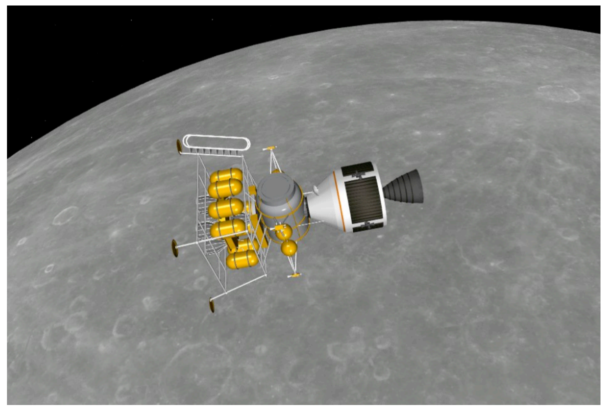

Figure 7: Orion/LSAM in Lunar Orbit

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