Ares I-X Requirements and Verification Lessons Learned

PM Challenge 2011

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Agenda

- Ares I-X Requirement and Verification Successes
- Independent Reviews
- Success factors
- Lessons Learned

Ares I-X Requirements and Verification Successes

- Successfully implemented system engineering best practices and used common formats and processes for requirement and verification development.
- Requirements and verifications had complete accountability (possessed ownership).
- Requirements were tracked and linked between all requirement levels.
- All verifications had a one-to-one traceability to requirements.
- Tracked and closed 100% of all system and element waivers prior to launch.
- Verified 100% of all system and element level requirements prior to launch.
- All verification artifacts configuration controlled.

Independent Reviews

Positive Lesson –

Independent reviews contributed extensively to the success of the mission.

- **Independent reviews provided a special oversight of processes and helped ensure mission processes are adhered to.**
- **Independent reviews provided an additional check that requirements are complete, well communicated and reduced the possibility of missing requirements.**
- **Independent reviews helped enforce issues to closure.**
- **Independent reviews are interested in your success and provide in-depth detailed reports in areas you may not have sometimes thought of.**
- **Ares I-X used independent reviews extensively for requirements and verification development.**

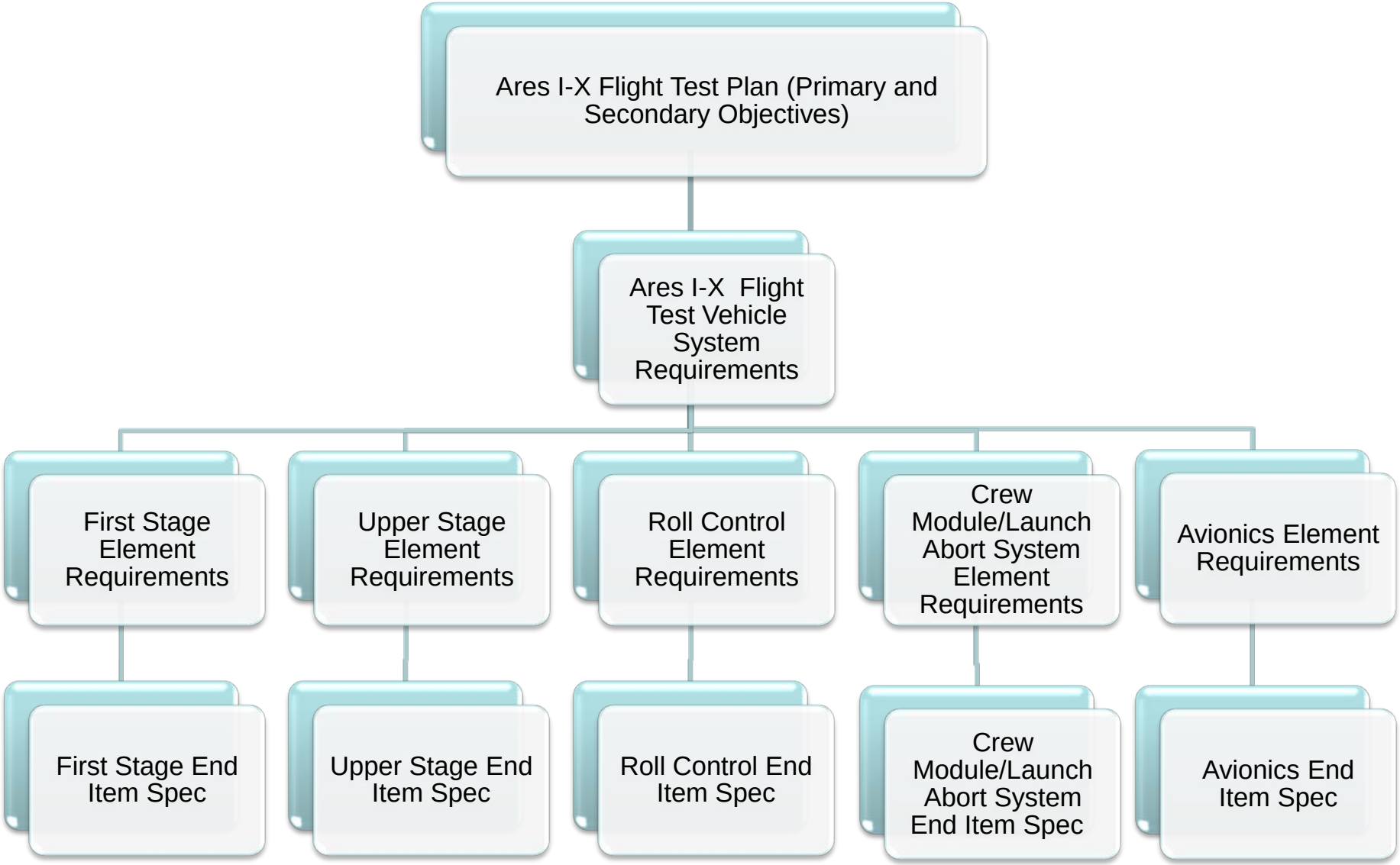
Success Factors:
Ares I-X Requirement Owners

- **Requirement owners were key to getting the right requirements developed and verified.**
- **Ares I-X had requirement owners at the system, element and contract levels.**
- **All verification activities had to be collaborated with the system requirement owners.**
  - **This provided insight to the verification processes two levels down for the system requirement owners.**
  - **Ensured that verification activities would meet system verification requirements.**

Success Factors:
Good System Requirements

- **SE&I followed best practices following the NPR 7123. 1 "NASA Systems Engineering Processes and Requirements".**
  - **This was implemented through the Ares I-X System Engineering Management Plan.**
- **Ares I-X SE&I modeled system requirements development after the CxP Requirements Engineering Management Plan (REMP) and followed the NASA System Engineering Handbook.**
- **Requirements were product oriented and well communicated through, working groups, SEMP, technical interchange meetings and summits.**

Requirements Flow



Success Factors: Verification Implementation Process

Verification is essential. Projects often write requirements and then later decide on how to verify them. This is significantly less effective as the time between the two activities increases.

- **Ares I-X verifications were developed upfront as the requirements were being developed and then assigned requirement owners.**
- **Requirement owners developed separate Verification Requirement Definition Sheets (VRDS) for each requirement.**

FTV-014 VRDS Example

Ares I–X FTV System
Verification Requirement Definition Sheet

FTV SRD Requirement to be Verified		
Verification Number: VR-FTV-014	**Requirement Number:** FTV-014	

Requirement Title: **True Heading**

Verification Requirements

Verification method: The maintenance of the true heading angle of 90 +/-2 degrees shall be verified by **Analysis**.

Description of verification activities to be performed: The Ares I-X Trajectory Lead shall perform an analysis of true heading. The analysis shall be done using a NASA approved 3-DOF non-linear flight dynamics model of the integrated vehicle. The analysis shall be done using nominal input values to provide a single nominal trajectory. The analysis shall determine the true heading angle of the vehicle as a function of time from pitch over to initiation of separation. The true heading analysis shall be peer reviewed by a panel that includes one or more independent experts.

Success Criterion: The verification shall be considered successful when the Analysis shows that the true heading angle does not deviate from the values specified in the FTV SRD during flight (from pitch over to initiation of separation) with a probability of at least 95%.

Rationale: It is not possible to adequately test the flight dynamical behavior of the FTV in a ground-based environment prior to launch, thus analysis must be used.

Verification Implementation

Level: FTV System FTV System Complies with FTV-014 (see attached compliance statement)

Applicable documents: Ares I-X FTV Control Algorithm & Parameters : AI1-SYS-CAP

Nonconformance history: None

Closure data/documentation required:

a. Ares I-X FTV Control Algorithm & Parameters (AI1-SYS-CAP),
b. Technical Quality Review Summary *Ares I-X Control Algorithm and Parameters for the Ares I-X Flight Test Vehicle*, AI1-SYS-CAP-V3.00 February 13, 2009

Event preceding Verification Activity: CDR Complete .
Estimated Duration of Verification Activity: _30__ Days

Compliance Statement Example

VR-FTV-014 Compliance Statement: Review of the analysis conducted and reported in the AI1-SYS-CAPv3.00 shows that the FTV is in compliance with SRD requirement number FTV-014.

FTV-014: True Heading

- *FTV-014:* The FTV shall maintain a 90 +/- 2 degrees true heading angle from pitch over to initiation of separation

  [Rationale: Given that the Ares I-X mission exercises the FS burn only, achieving approximately Mach 4.5, there are no orbital parameter requirements. Thus, the FTV will follow a "due East" profile over the Atlantic Ocean upon launch. This sets up FS recovery that meets P3 Test Objective.]

Comparisons of nominal and dispersed heading (psi) have been made with all the analysis tools and are documented in the AI1-SYS-CAPv3, Chapter 9. Figure 1 (from page 169) shows the nominal heading errors throughout the flight stay less than 1 degree for all analysis tools.

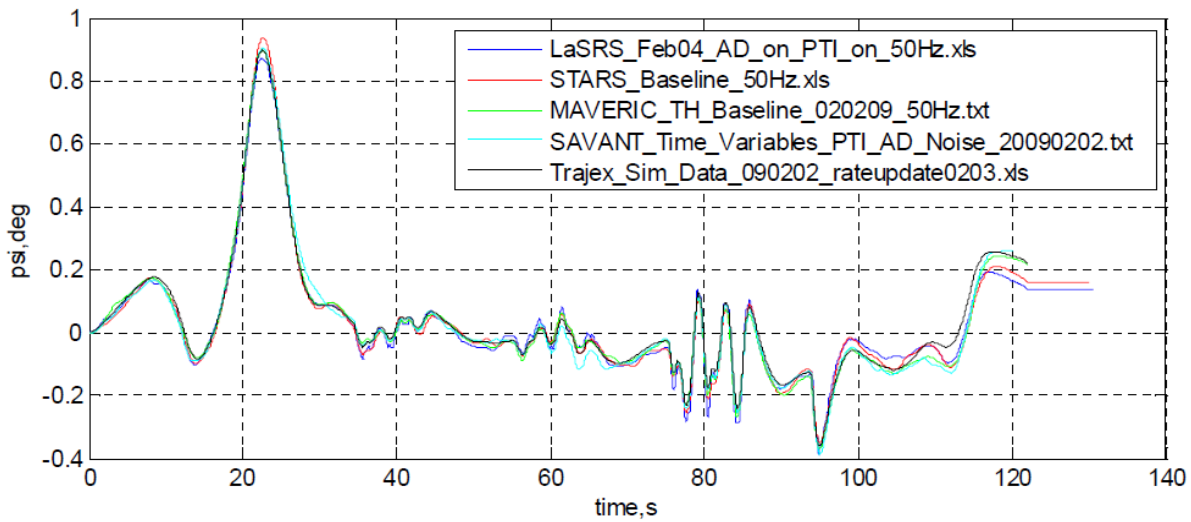


Figure 1 Heading, degrees off target azimuth.

VRDS Example cont…

Trace analysis

The following children requirements and artifacts traced to FTV-014:

AVI-017(Control Algorithm [Baseline]) ***CR-AIX-0588, Approved at XCB 20091006***

FS-005(Thrust Vector Control) ***FS-005-ELEC_ARES I-X-VSS-003 , Approved at XCB 20091006***

FS-005-INT(STAGE)_ARES I-X-VSS-013 , Approved at XCB 20091010

Review of Artifacts and Closure reports

1. AIX-SYS-CAP
https://ice.exploration.nasa.gov/Windchill/netmarkets/jsp/document/download.jsp?oid=document%7Ewt.doc.WTDocument%3A985878235&u8=1

2. Peer Review Documentation of AI1-SYS-CAP
https://ice.exploration.nasa.gov/Windchill/netmarkets/jsp/folder/view.jsp?oid=folder%7Ewt.folder.SubFolder%3A1616820362&u8=1

3. VRDS-AVI-017
https://ice.exploration.nasa.gov/Windchill/netmarkets/jsp/folder/view.jsp?oid=folder%7Ewt.folder.SubFolder%3A1485222456&u8=1

4. VRDS-FS-005
https://ice.exploration.nasa.gov/Windchill/netmarkets/jsp/document/download.jsp?oid=document%7Ewt.doc.WTDocument%3A985878235&u8=1

Success Factors:
A Different Interface Development Approach

- Ares I-X did not use the typical role of Interface Requirement Documents (IRDs) to define requirements for interfaces or use Interface Control Documents (ICDs) as the solutions to the IRDs.
- IRDs were considered developing ICDs. ICDs were considered established interfaces under configuration control.
- This process was easier to manage.
- Key success factor was including rationales (justification) for each interface definition and any associated agreements negotiated by requirement owners (helped determine roles and responsibilities during interface development).

Requirement and Interface Flow Example

FTP

- Starting with: Flight Test Plan Primary and Secondary Objectives **P1-P5, S1-S7**
- Specific Flight Test Plan **Constraint 5.1f** states, " To minimize development costs, booster avionics components should be primarily Space Shuttle RSRM heritage whenever possible."

FTV SRD

- ***FTV – 097***: The FTV shall use the Space Shuttle Solid Rocket Booster (SRB) heritage Thrust Vector Control (TVC) System.
- *[Trace: **P1-P5, S1-S7, FTP Constraint 5.1f**]*
- *[Allocation: FS, Avionics] Note: A check on allocations show that there is also a monitoring interface requirement needed. (FS-197 Thrust Vector Control Monitoring)*

FS ERD

- ***FS – 005***: The First Stage shall utilize the SRB heritage TVC subsystem designed in accordance with specification 10CEI-0001.
- *[Trace: **FTV - 097**]*
- *[Allocation: Propulsion]*

Propulsion End Item Spec

- Specification 10CEI-0001 " Part I Integrated Solid Rocket Booster for Operational Flights"
- *[Trace: **FS -005**]*
- *[Allocation: N/A (reached the bottom of the product hierarchy)]*

Ares I-X Interface Example from FTV-097

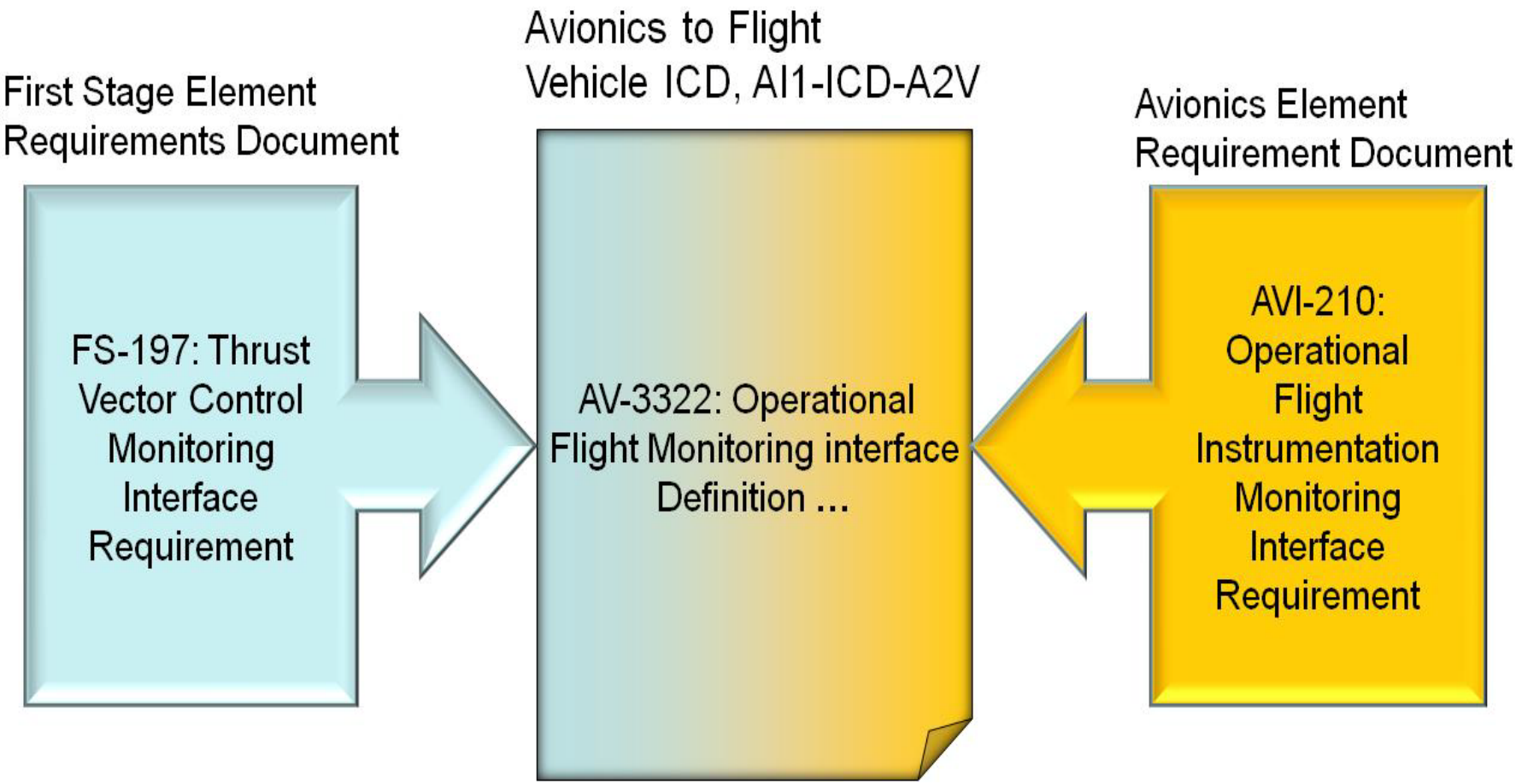
➢**AVI-210: First Stage – Thrust Vector Control Operational Flight Instrumentation Monitoring Interface.**
The avionics shall provide Operational Flight Instrumentation Monitoring with the First Stage Thrust Vector Controller as describe in interface ID [AVI-3322] of the Avionics to Flight Vehicle ICD, AI1-ICD-A2V.
[Rationale: A portion of Lockheed heritage avionics will be installed and interfaced with the First Stage Thrust Vectoring hardware requiring an interface definition for mating the monitoring system and ensuring compatibility between FS and the Avionics Elements .]
[Trace: FTV-097]
[Allocation: AIS, SDA]

➢**FS-197 Thrust Vector Control Monitoring Interface**
The First Stage shall use Operational Flight Instrumentation Monitoring as described in interface ID [AVI- 3322] of the Avionics to Flight Vehicle ICD, AI1-ICD-A2V.
[Rational: Per the Flight Test Plan, the Ares I-X will use heritage to the highest extent possible. The Thrust Vector Control Operational Flight Instrumentation is part of the Avionics heritage as agreed to in the Lockheed contract. First Stage will need to be compatible with this monitoring system.]
[Trace: FTV-017, FTV-097]
[Allocation: Thrust Vector Controller]

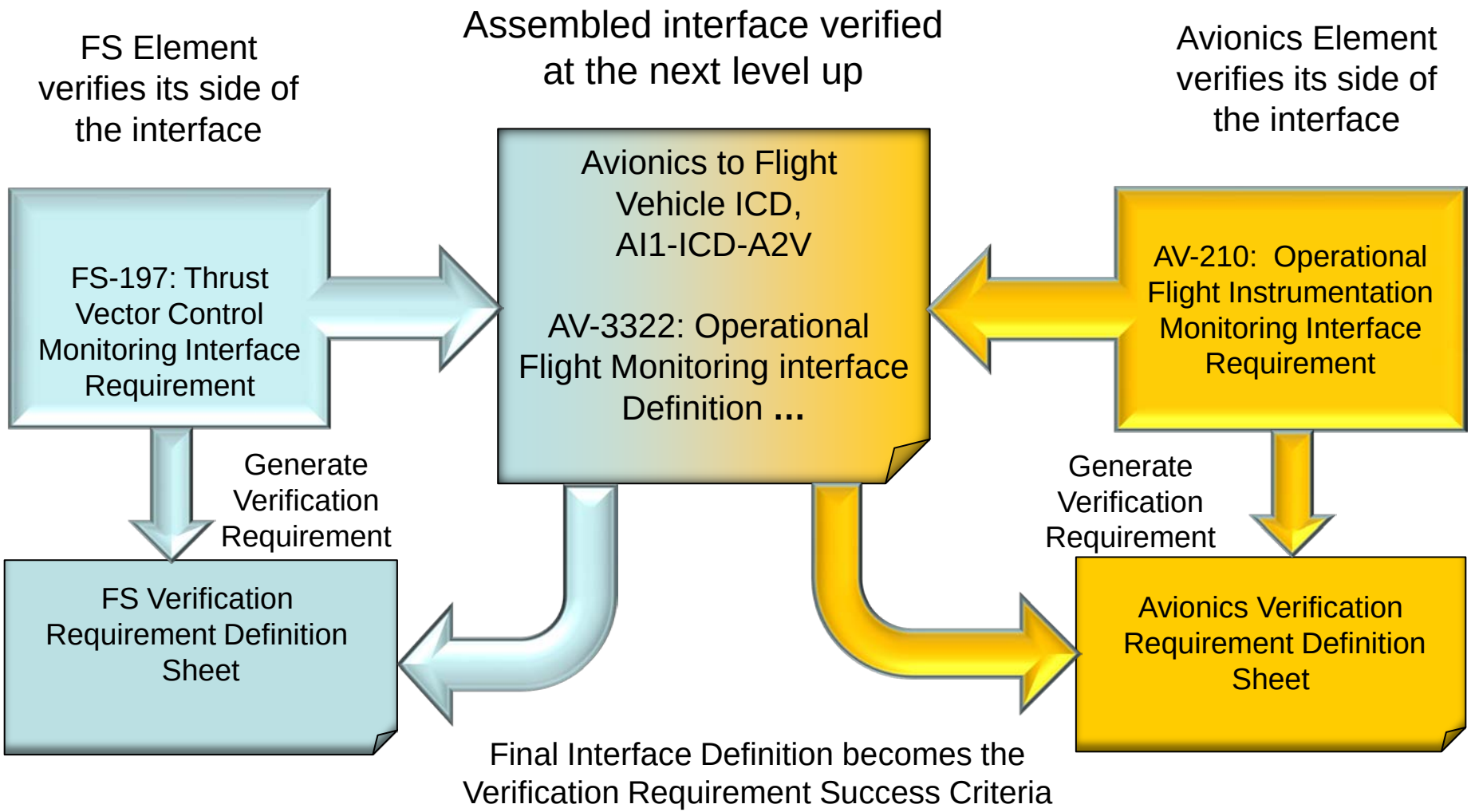
Avionics to Flight Vehicle ICD, AI1-ICD-A2V

➢**AVI-3322: Operational Flight Instrumentation Monitoring Interface**
The Operational Flight Instrumentation Monitoring system for Thrust Vector Control , FSS and OPT are the following per Table B – 10, Table B – 12, Table B – 15 and Table B - 17 through B - 20, Appendix B. Ignition S&A functions by Ground Command, Communication and Control (GC3) are shown in Table B - 11, Appendix B. A listing of OFI measurements are found in the Ares I-X DFI/OFI Measurement List (Document #AI1-SYS-DFI) …

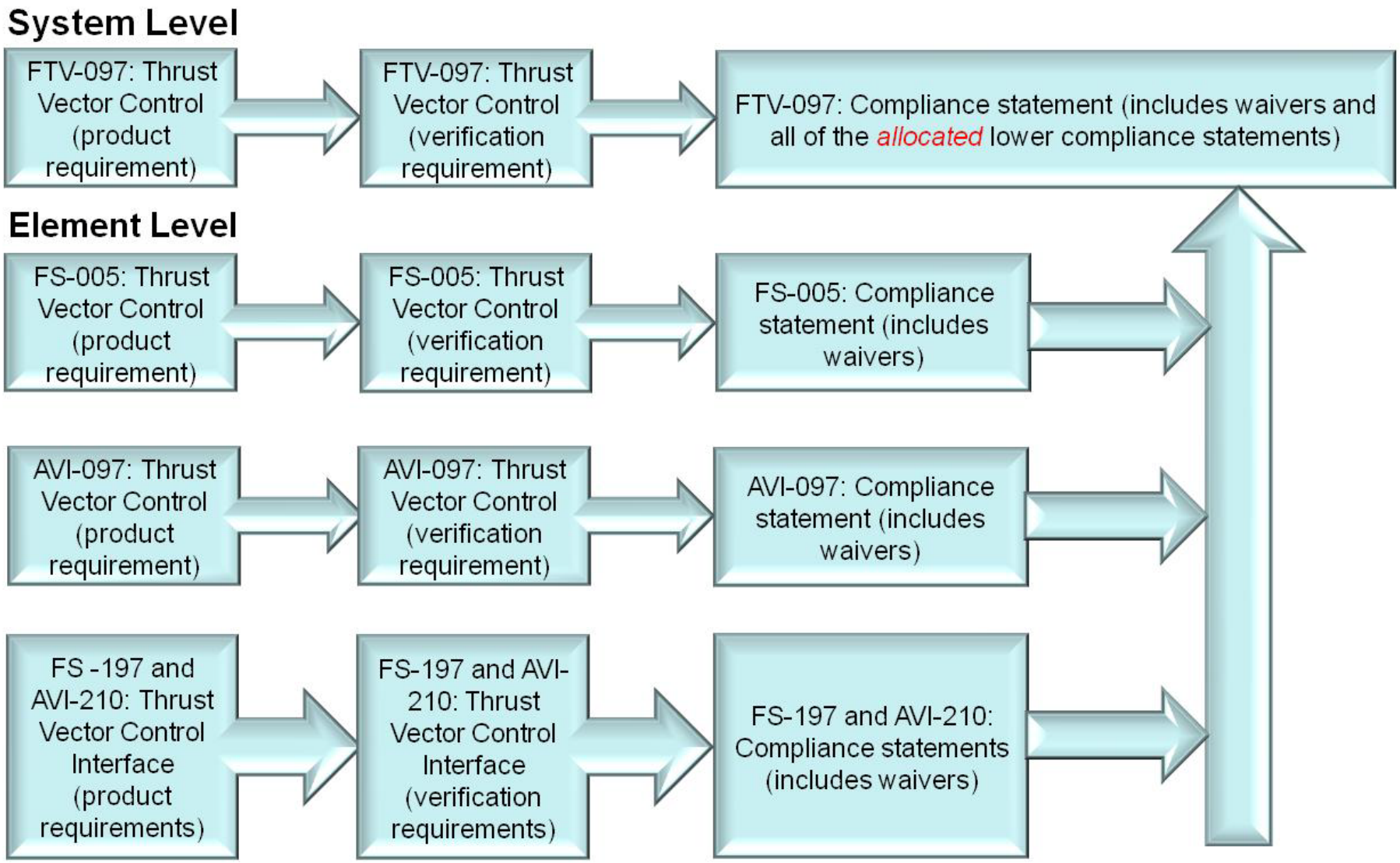
Interface Requirement Development



Interface Requirement Flow through Verification Example



System Verification Flow Example



Success Factors: Configuration Management

- Processes of approval and acquiring document baselines were well defined.
- All system and element level requirements and change requests, interfaces, verifications, drawings, procedures, waivers and analysis went to the Ares I-X Control Board (XCB) for approval.
- The XCB used board member voting instead of document signatures for approval.
  - This reduced turn around time and allowed for rapid decision making.
  - Votes were recorded and often replaced signatures.
  - SE&I was well represented and a member of the XCB.
- A key to the Ares I-X success was the tracking, configuration control and closure of all verifications and waivers prior to launch.

Success Factors: Mission Management and SE&I Co-location

- The Ares I-X Mission Manager co-located with SE&I during the system engineering development phase.
- The Ares I-X Mission Manager and SE&I Chief co-located with ground operations and the launch vehicle integration team during the system assembly, integration and launch phase.
- This led to a well informed management, improved communications and team direction, and enhanced the capability to make decisions rapidly.

Lessons Learned – Systems Engineering & Integration (SE&I)

- **Lesson**
  - It is important to have SE&I buy-in early in mission formulation. Otherwise you can lose control over the system processes. Ares I-X SE&I was set up after IPTs and contracts were in place which made it difficult early on to get complete collaboration over system processes.
- **Recommendation**
  - Establish SE&I's role at the beginning of the mission.
    - Key: Need to link IPT contracts (prime contractors) to address both the IPTs and the SE&I roles, processes and requirements – this will be difficult.
    - If contracts are already in place then the contract must be set up to allow incorporation of SE&I's role and processes.
  - Co-locate SE&I managers or leads as soon as possible with other IPTs to ensure that SE&I processes are understood and also to take advantage of other cultural processes.

Lessons Learned – Product versus Design Verifications

- **Lesson**
  - Need to identify where product or design verification apply.
    - Affects when verification paper closure occurs.
    - Affects quality of engineering documentation at CDR.
    - Affects acceptance reviews.
  - Drawings are not a substitute for “as built” documentation.
- **Recommendation**
  - Better communication and agreement on what product verification is versus design verification.
    - Need to have Inspection reports or “as built” documentation as part of the Acceptance Data Package.
    - Be open to other methods of verification practiced by industry.
    - Recognize the impact of verification plans on contracts and pre-engage with contractors and other centers on how verification processes will be supported.
    - Get understanding and buy-in for your verification plan.

Lessons – Verification Requirements Closure

- **Lesson**
  - Required heroic effort at the end to close all Verification Definition Requirement Sheets (VRDSs) at the element and system levels. This was due to misunderstanding the verification implementation process and culture differences.
- **Recommendation**
  - Baseline a system level verification implementation plan by PDR.
    - This is not a part of current NASA PDR Exit Success Criteria.
    - Take advantage of "Lean Event" activities between SE&I and IPTs to develop and agree to verification implementation.
    - Get culture buy-in.
  - Provide detailed examples of the verification implementation process.
  - Work on closing out, as many as possible, verifications at acceptance reviews. In theory they should all be able to be closed at acceptance reviews.

Lessons Learned – System Requirement Owners

- **Lesson**
  - Insufficient SRO resource loading early on led to some requirements not having ownership to very late in the development and delayed closure some lower level verifications.
  - SRO availability for verification reviews often had time conflicts with other competing tasks.
- **Recommendation**
  - Have SROs committed starting from requirement development.
  - Select SROs that can provide support through verification.
  - Tap IPT opportunities to act as SROs.
  - Balance SRO workload.
  - Ensure that newly delegated SROs have the appropriate engineering discipline and background knowledge to hit the ground running.

Lessons Learned – Waivers

- **Lesson**
  - Retrieving all waivers associated with a requirement was challenging. This was due to improper set up of database fields.
- **Recommendation**
  - Ensure that specific field in the verification database can link waivers to requirements.
  - Run test scenarios on the waiver process.

Lessons Learned – Tools

- **Lesson**
  - **Had difficulty tracking and managing requirements on the mission database.**
    - **Could not obtain requirement link analysis reports.**
    - **Not localized and therefore turn around for reports were slow.**
  - **The mission data repository was slow in retrieving files (software flaw) in addition to poor directory structure prevented fast file searches and retrieval.**
- **Recommendation**
  - **Know your data management tools.**
    - **Provide sufficient training to users.**
    - **If possible, database entry needs to be local to the technical team.**
    - **Move data management as a technical process under SE&I.**
    - **Develop better directory structures.**
      - **A study of other successful product data management directories should be conducted and a directory model selected.**
  - **On complex and large projects an efficient data repository is essential. A trade study should be conducted to select the best data repository for the mission.**

Summary

- Ares I-X was a highly successful mission.
- Using best requirements and verification practices played a large part in the success of Ares I-X.
- Ares I-X Requirements and Verification Lessons Learned along with all the Mission Lessons Learned have been reported, shared, and archived.
- Ares I-X Systems Engineering and Integration team will be receiving the prestigious “NASA Systems Engineering Excellence” award at this year’s 2011 PM Challenge.
- The engineering and management success, complexity and innovation of Ares I-X led Time Magazine to select Ares I-X as the “Invention of the Year” for 2009.

Acronyms

- CxP – Constellation Program
- CDR – Critical Design Review
- IPT – Integrated Product Team
- PDR – Preliminary Design Review
- SE&I – System Engineering and Integration (under Ares I-X)
- SRO – System Requirement Owner
- VRDS – Verification Requirement Definition Sheet