Atlas Emergency Detection System (EDS)

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[Abstract] The Atlas Expendable Launch Vehicle Program has been studying safe abort requirements and is being considered as the logical choice to provide flight-proven, low risk, low cost Earth to Orbit transportation for a number of commercial human spaceflight applications. Key to the success of these commercial entrepreneurial endeavors is to ensure that the Atlas system provides the utmost abort safety by providing insight into the performance and health of the launch vehicle systems. Atlas has designed key aspects of an Emergency Detection System (EDS) and has a test plan in place to begin demonstration of this system. This Paper describes the rationale that was used to baseline the set of safety critical measurements that are required that make it a critical addition to the flight-proven Atlas system to enable commercial human spaceflight.

The EDS will be added as a bolt-on kit to the standard Atlas and will be used to detect imminent vehicle failures and to initiate an abort. The EDS will monitor the launch vehicle, detect anomalous conditions, safe the vehicle, and send the abort signal. As a bolt-on kit, the EDS will not affect the proven Atlas V vehicle design. The Paper will provide insight into the detailed fault coverage assessment process that was performed to identify the safety critical failure modes, the time for those failures to result in a catastrophic situation, and the primary, backup & corroborating measurements that would be monitored for those failure modes. This analysis formed the set of measurements that will be monitored by the EDS. This analysis was not unusual for Atlas, as the building blocks of an EDS system for Atlas are flying today. For example, Atlas currently uses extensive RD-180 engine health checks that occur prior to liftoff. There are Pogo detection and correction algorithms and propellant utilization optimization software in place today.

Finally, the Paper will detail the operational and abort philosophies utilized by the EDS to optimize abort conditions. For example, there may be aborts that could be enhanced by optimizing the inherent throttle capabilities of the RD-180 engine. Aborts could also be improved by tailoring the basic ascent trajectories to minimize exposure to Atlantic abort conditions.

The Atlas Expendable launch vehicle is a mature system with demonstrated design robustness and processes discipline that provides the foundation for a highly reliable, robust solution for commercial human spaceflight needs. The EDS can be flown on every Atlas mission, providing critical system characterization and demonstration before the first EDS flight.

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I. Background

An Emergency Detection System (EDS) is a crucial addition to any launch system that will carry humans. The EDS requirements are very simple: detect imminent vehicle failures and initiate an abort. This simple requirement is intuitive, but very difficult to design and implement. An intimate knowledge of the failure modes and vehicle response is not a trivial assessment. Flight-proven systems have a significant advantage in this assessment, as their system and subsystem performance is well understood and characterized, thus providing a firm foundation from which an EDS can be designed.

The Atlas Expendable Launch Vehicle is a flight-proven system with a long heritage of mission success. Extensive failure analysis has been completed during the development of the Atlas. As such, Atlas provides an excellent system from which an EDS can be designed and flight tested prior to the first operational mission. The EDS can be implemented incrementally to improve overall Atlas reliability, but also to demonstrate key attributes of the system prior to the first operational mission.

II. Requirements

A fundamental understanding of abort requirements is required in order to start the development of this system. The key driving requirement is that the launch vehicle systems must be single fault tolerant to loss of mission, and dual fault tolerant to loss of life. This is difficult to meet on vehicles with single engines, feedlines, pressure bottles and similar systems. As such, a system-level approach must be invoked in order to determine all failure modes, the likelihood of those failures, and the system-level result if the failure is realized. Once that is determined, methods to sense those failures modes must be developed.

The primary EDS design effort concentrated on determining and screening the input parameters to the EDS. These input parameters are needed in order to determine the type of capability that will be required in the EDS hardware components.

EDS must sense mission critical failures, safe the launch vehicle and initiate the abort command. EDS should have as much flexibility as possible to improve abort conditions. For example, if the mission cannot be completed due to a critical system failure, but loss of life is not imminent, EDS response can be tailored to issue an abort/separation command at a time providing the greatest chance for survivable abort. Additionally, if a catastrophic failure of a critical system is imminent, EDS will initiate abort immediately

Atlas has performed a detailed fault coverage assessment that identified 1) Safety critical failure modes; 2) Time for those failures to result in a catastrophic situation; and 3) Primary, backup & corroborating measurements that would be monitored for those failure modes. This type of assessment is not unusual for Atlas, as the building blocks of an EDS are flying today for RD-180 engine health check, in the propellant utilization system, the spacecraft separation tumble check, in the control sensor redundancy handling (triple and dual redundant sensors), vehicle health fault monitoring (active mode during preflight and passive mode during flight), and in the flight-demonstrated Block 2 Avionics control redundancy management.

III. Groundrules and Assumptions for Parameter Selection

In order to develop the simplest, most robust and reliable EDS, the following key Groundrules were established for the parameter selection process:

1. Minimize the number of parameters as much as practical to minimize the possibility of a false abort. The more parameters that are monitored increases the complexity of the EDS, and the potential for anomalous indications of failures that will lead to an abort.
2. Parameters must support detection of catastrophic faults requiring immediate abort
3. A minimum of two independent indications must be included for a baselined parameter in order to provide redundancy of key parameters. This will prevent a false abort by requiring confirmation from a minimum of two redundant sensors or a primary sensor and a backup corroborating sensor prior to initiating any abort/separation.

4. Existing Atlas ground operations will not be impacted by the implementation of the EDS. The existing Atlas ground system already monitors critical items and will safe the vehicle before engine start.
5. After engine start, parameters must support detection of early degradation in a critical Booster or Centaur system to command an early or later abort.
6. Passive EDS parameter monitoring will be done on as many flights as possible prior to the first operational mission. This allows for more extensive vehicle characterization and EDS parameter limit development and definition.
7. Minimize the criteria/parameters involved in abort initiation to simplify the system design. This equates to using the highest system level detection possible (i.e., vehicle rates, tank pressures, etc) for non-catastrophic faults, and use component lower-level detection only when necessary.
8. Use Orbital Space Plane (OSP) Fault Coverage Assessment results. An extensive failure mode analysis was completed during the OSP Program and has formed the basis for the current Atlas EDS baseline design.
9. Consider past abort initiation vehicle parameters. As a check, the results of the EDS parameter screening process was compared against previous expendable launch vehicle abort system experience (Mercury/Atlas, Gemini/Titan and Apollo). Common parameters were automatically included in the EDS baseline.

Failure of subsystems or components whose effect could result in loss of life falls into two categories:

1. Single Point Failures (SPF) that must be monitored by the EDS, or
2. Subsystems that contain SPFs that must be subjected to and pass a defined Design For Minimum Risk (DFMR) screening process.

In the first case, the SPF must be monitored for "Higher-level" (system-level) or "Lower-level" (sub-system/component) detected failures via key parameters. In the second case, the DFMR process will capture design margin of safety and demonstrated test margin which provides the requisite level of confidence in the subsystem that eliminate the needs for EDS monitoring. The DFMR screening considers a variety of situations including SPF components that cannot be monitored with exiting vehicle sensors, or the method of detecting a failure is considered fairly complex relative to abort system designed limits leading to concerns of increasing the opportunity for a false abort. In the process of completing the Fault Coverage Assessment, subsystems were identified as candidates for a DFMR screening, and identified the type of instrumentation required to monitor the fault condition if new instrumentation was necessary. In order to design in future EDS growth due to unforeseen future DFMR screening, the EDS has been designed to accommodate up to 32 additional signals.

IV. Technical Evaluation

With these groundrules and assumptions, all parameters were categorized as either "Higher-level" monitoring parameters or "Lower-level" parameters. The "Higher-level" parameters monitored included Manually Initiated Engine Shutdown (manual abort/separation commands), Flight Termination System (shutdown/destruct commands), low booster and upper stage tank pressures, excessive vehicle rates (Pitch, Roll), excessive autopilot generated attitude errors (Pitch, Yaw, Roll), vehicle related engine performance indications (chamber and injector pressure, shaft speed/displacement, duct temperatures), and electrical power/vehicle control capability health. These "Higher-level" parameters were compared with previous expendable launch vehicles with similar EDS systems (Mercury, Gemini, Apollo) and common parameters were immediately baselined in the Atlas EDS.

The remaining parameters were designated as "Lower-level" parameters and included degrading non-fault tolerant subsystems or components whose effect can be projected into a future loss of mission event. These critical systems involved predicting a catastrophic situation in flight such as within the Tank Pressurization Source Subsystem or the LO2 propellant flow to the engine.

In all cases, the parameter screening process was accomplished very selectively and utilized a common approach. That approach is summarized on Figure 1.

V. Results

The Atlas EDS baseline includes a total of 76 parameters to be monitored, 37 on the booster and 39 on the Upper Stage. These are all existing parameters and are summarized below. In all cases, the data will be acquired from the redundant 1553 bus data and will use existing dual or triple redundant sensors.

"Higher-level" parameters:
1. Vehicle rates (Pitch, Yaw, Roll) that will provide a high level indication of loss of vehicle control
2. Tank Pressures sensors that will provide a high level indication of propellant feed system health
3. Vehicle Attitude Errors corroboration to vehicle rates that will provide high level indication of loss of vehicle control
4. Critical power and control capability (Command errors and timeouts, Fault Tolerant INU Health, and flight Watch Dog Timers) that will provide high level indication of power availability for system control and command capability health
5. Range Safety Officer initiated engine shutdown and destruct to provide safe abort prior to destruct command (includes 4 discretes)
6. Manually initiated engine shutdown and separation from redundant 1553 bus and hardwired interface to provide crew in the loop decision capability
7. Thrust / Engine Performance/Degredation in both the booster and upper stage engines (RL10 – Chamber pressure and LH2 injector inlet pressure; RD180 – Hot gas duct temperature, LOX shaft displacement, MTU shaft speed)

"Lower-level" parameters:
1. LOX starvation via redundant 1553 bus Booster Stage Propellant Utilization sensors to provide immediate or delayed abort decision capability prior to Booster Engine Cutoff (BECO)
2. Booster pneumatic and pressurization control sensors to provide immediate (catastrophic) or delayed abort decision.

As a sanity check, the results of the screening process were compared against previous expendable launch vehicle abort system experience (Mercury/Atlas, Gemini/Titan and Apollo). Table 1 highlights the comparison of Atlas EDS and Mercury "ASIS" systems.
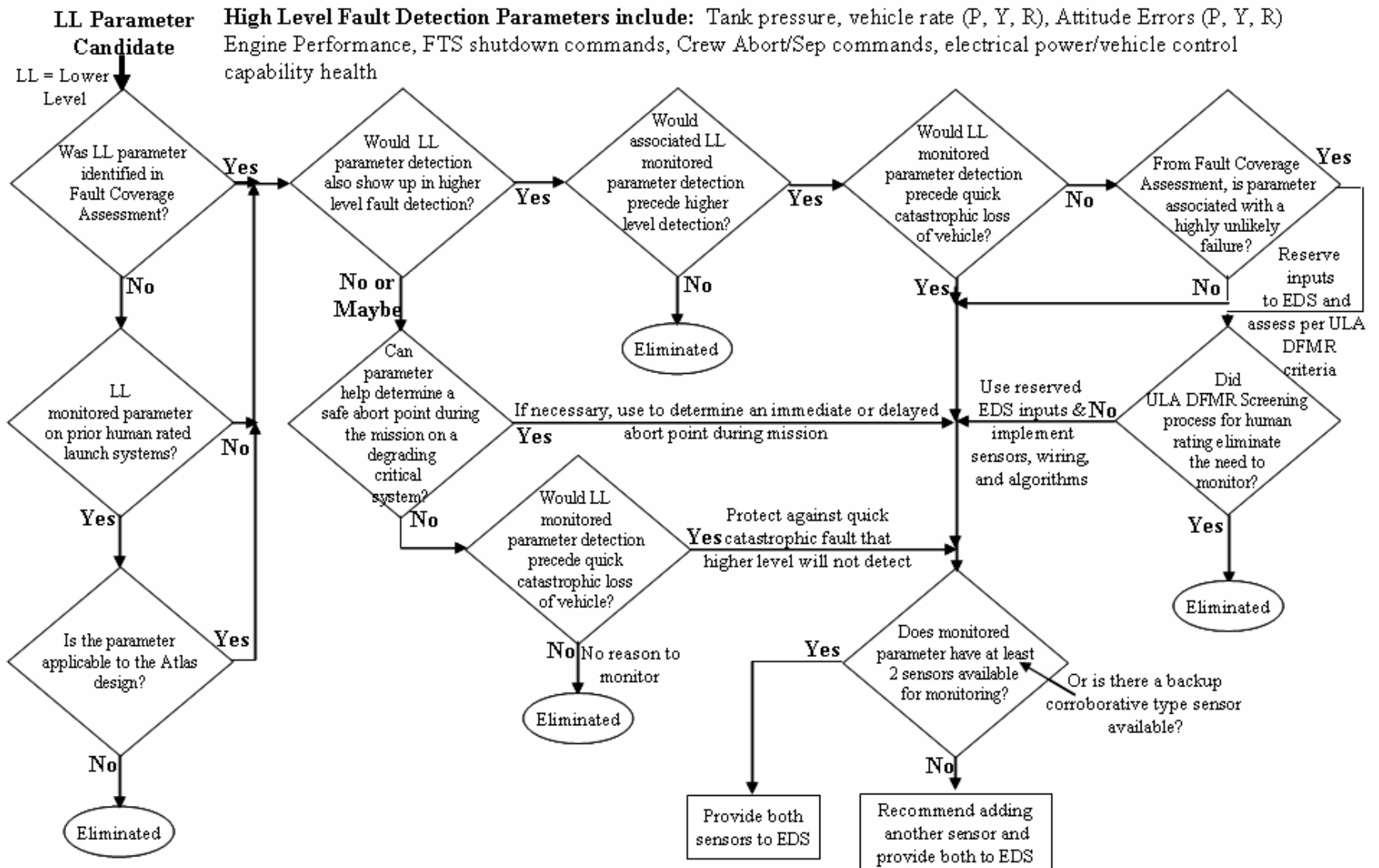
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LL Parameter Candidate

LL = Lower Level

High Level Fault Detection Parameters include: Tank pressure, vehicle rate (P, Y, R), Attitude Errors (P, Y, R) Engine Performance, FTS shutdown commands, Crew Abort/Sep commands, electrical power/vehicle control capability health

Was LL parameter identified in Fault Coverage Assessment? — **Yes** / **No**

LL monitored parameter on prior human rated launch systems? — **Yes** / **No**

Is the parameter applicable to the Atlas design? — **Yes** / **No** → Eliminated

Would LL parameter detection also show up in higher level fault detection? — **Yes** / **No or Maybe**

Can parameter help determine a safe abort point during the mission on a degrading critical system? — **Yes** / **No**

If necessary, use to determine an immediate or delayed abort point during mission

Would LL monitored parameter detection precede higher level detection? — **Yes** / **No** → Eliminated

Would LL monitored parameter detection precede quick catastrophic loss of vehicle? — **Yes** / **No** — No reason to monitor → Eliminated

Protect against quick catastrophic fault that higher level will not detect — **Yes**

Would LL monitored parameter detection precede quick catastrophic loss of vehicle? — **Yes** / **No**

From Fault Coverage Assessment, is parameter associated with a highly unlikely failure? — **Yes** / **No**

Reserve inputs to EDS and assess per ULA DFMR criteria

Use reserved EDS inputs & implement sensors, wiring, and algorithms — **No**

Did ULA DFMR Screening process for human rating eliminate the need to monitor? — **Yes** → Eliminated

Does monitored parameter have at least 2 sensors available for monitoring? Or is there a backup corroborative type sensor available? — **Yes** / **No**

Provide both sensors to EDS

Recommend adding another sensor and provide both to EDS

Figure 1. Atlas EDS Parameter Screening Process. *The Atlas Program utilized a rigorous, consistent, thorough process to methodically evaluate all parameters that were considered for the EDS*

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- **Assuming two sensors for each parameter on Mercury (20 Total for a single stage)**
  - ➢ Roll Rate (Primary & Backup)
  - ➢ Pitch Rate (Primary & Backup)
  - ➢ Yaw Rate (Primary & Backup)
  - ➢ LO2 Tank Pressure
  - ➢ LO2/Fuel Tank Differential Pressure
  - ➢ Fuel Manifold Pressure Booster Engine 1
  - ➢ Fuel Manifold Pressure Booster Engine 2
  - ➢ Fuel Manifold Pressure Sustainer Engine
  - ➢ Hydraulic Pressure
  - ➢ Power

  Note steering was not accomplished via an inertial guidance system on the Mercury vehicles

Atlas V proposed EDS parameter totals

– **Booster Stage (37 Total)**
- LO2 Tank Pressure (1553) Triple Redundant (3)
- Fuel Tank Pressure (1553) Triple Redundant (3)
- LO2 Delta P-PU Pressure (1553) Triple Redundant (3)
- RP1 Delta P-PU Pressure (1553) Triple Redundant (3)
- MTU Shaft Speed (1553) Triple Redundant (3)
- RRGU 1 Pitch Rate (1553) Triple Redundant (3)
- RRGU 2 Pitch Rate (1553) Triple Redundant (3)
- RRGU 1 Yaw Rate (1553) Triple Redundant (3)
- RRGU 2 Yaw Rate (1553) Triple Redundant (3)
- 1553 bus communication timeout on primary and backup (2)
- Watch Dog Timers (2)
- COPV Pressure (2)
- Engine Shaft Displacement (2)
- Engine Hot Gas Duct Temperature (2)

– **Upper Stage (39 Total)**
- LO2 Tank Pressure (1553) Triple Redundant (3)
- Fuel Tank Pressure (1553) Triple Redundant (3)
- IMS – Filtered Pitch Rate, Pitch Attitude Error (2)
- IMS – Filtered Yaw Rate, Yaw Attitude Error (2)
- IMS – Filtered Roll Rate, Roll Attitude Error (2)
- Watch Dog Timers (2)
- 1553 bus communication errors/FTINU Health (15)
- FTS engine shutdown (4)
- Crew Abort (4)
- Engine Pressures (2)

- **Atlas V booster totals without triple redundancy (28 total)**

- **Atlas V upper stage totals without triple redundancy (37 total)**

Given changes in the method of vehicle control during flight and addition of triple redundancy to the vehicle control transducers, recommendation is in line with Mercury implementation

Table 1. Comparison of Atlas EDS Parameters with Mercury/Atlas Parameters. *The Atlas Program compared the results of the parameter screening process with the Mercury Atlas Program ASIS parameters as a sanity check.*

VI. Implementation

The baseline set of higher and lower level parameters reflect a relatively simple level of complexity, based on our extensive knowledge of the Atlas system and heritage expendable launch vehicle abort system experience. Existing triple redundant sensors are being used extensively and the data will be available from the redundant 1553 data bus. Each has multiple health-type checks completed prior to liftoff. From the perspective of design complexity, no new sensors are required to meet the EDS Groundrules and Requirements. Existing spares capability will be used on the RD-180, along with minor wiring changes, bus couplers and 2 new watch dog timers. The RL10 will require some minor wiring changes, two new watchdog timers, and additional wiring and couplers. No changes to the existing method of checking out each sensor, only additional checkouts may be required for the same checkout. Flight algorithms similar to those flying now will be used extensively, leveraging other existing algorithms from triple redundant sensors. Dual redundant sensors will be based upon existing techniques used for past ground or airborne algorithms. We will utilize our extensive experience in the use of redundant sensors to ensure EDS implementation will not be blazing new trails. Lastly, checkout of the EDS will be accomplished in using our proven SIL and FASTER hardware in the loop testing plus demonstration flights with EDS in a monitoring/telemetry mode only to provide the highest level of confidence prior to the first operations EDS missions.

VII. Conclusion

Identifying the required parameters to be monitored for an Atlas EDS system for commercial human spaceflight has been successfully accomplished. The Atlas Fault Coverage Assessment and the results of the rigorous parameter screening process result in a system that meets all Requirements, Groundrules, and Assumptions. The results demonstrate that the EDS will be required to monitor 76 existing measurements. These measurements are used on existing Atlas Launch Vehicles and that data is being collected and characterized on each mission. No additional EDS parameters are required, thus significantly reducing the development and qualification time for this system to be flown on Atlas. In addition, the extensive Atlas flight history database can be used to exercise the EDS during ground testing, thus providing an unparalleled level of confidence in this safety-critical system prior to the first operational mission.