GLOBAL HAWK

A Study of a Reconnaissance Surveillance Vehicle

TIER II + UAV GENESIS

- OPERATION DESERT STORM POINTED OUT AN ISR SHORTFALL
- THIS NEED TRANSLATED INTO DEVELOPING ISR SYSTEMS WHICH PROVIDE CONSIDERABLE:

  - REACH
  - PERSISTENCE

    AND …

  - ELIMINATES DIRECT PERSONAL INTERACTION

GENERAL UAV ISSUES

UAV Design

- **UAV Designs have the following attributes embedded:**

  - AUTOMATION
  - PARTIAL AUTONOMY – *thus need for Ground Segment*

ULTIMATE OBJECTIVE IS TO EVOLVE TO … FULL AUTONOMY

- **THE CONSEQUENCES OF THIS DESIRE:**

  - LIABILITY
  - CERTIFICATION
  - SAFETY
  - RELIABILITY
  - AFFORDABILITY
  …

UAV Operating Domains

MILITARY

STRATEGIC

- Worldwide OPS
- Self ferry / refuel
- Robust Nav
  - Quad / dissimilar
  - GPS / DGPS
  - Inertial INS (high – quality)
- ICAO / GATM
- Robust COMMs
- Over-flight rights

TACTICAL

- In -Theater Use Only
- Transport to theater
- Robust Nav
  - GPS
  - Inertial INS (high – quality)
- Robust COMMs

CIVILIAN

COMMERCIAL

- Requirements moving towards same as Manned

Risk Reduction

- Develop from Experience
- Minimize Non-recurring Development
- Test early
- Design for future growth

Risk Reduction

- **Never attempt to incorporate more than 2 major technological advances at one time**
- **Thus minimal engine development for this application was a must**
- **The major remaining risks were:**
  - **Large scale system integration**
  - **Software development**
  - **Sensor / Comms development and integration**

System Reliability - Flight Critical

Reliability	Complexity	# Flt Computers	Example	Availability
10^{-09}	$$	• Quad	• Airliner (150M- 500M)	
10^{-07}		• Triple	• Fighter (50M – 150 M)	
10^{-05}		• Dual / Triple	• Moderate Cost UAVs (10M – 50 M)	
10^{-03}		• Single / Dual	• Reusable UAVs Expendables (300 K –10 M)	

Design to Cost

Lowest costs are achievable by:

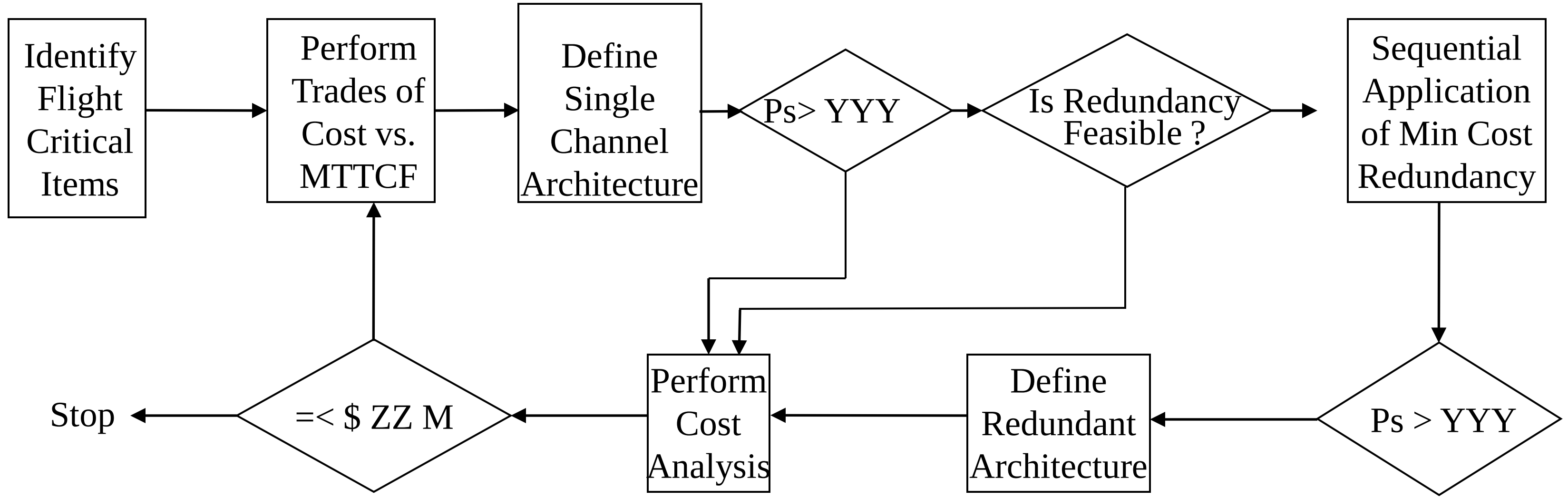
- Simple but redundant systems
- Use of parts from existing designs
- Use of COTS hardware wherever possible
- Tailor requirements to avoid over-design
- Use of strategically placed sensors for system status
- Use of smart s/w to limit, control, and “heal” failures

Cost considerations must be applied from part design through testing and onto system tests.

Reliability Trade Methodology

Optimize Reliability / Redundancy Consistent with Cost Constraint

Requirement: Desired Loss Rate of Less than 1 Per XXX Missions, **(** Ps > (1- $\frac{1}{XXX}$)**)**



Redundancy

- **Level of Redundancy – Application dependent / Cost**
- **Mostly Similar / Some Dissimilar**
  - **Flight Critical / Mission Critical**

Flight Critical

- **Nav Equipment**
- **Flt Computers**
- **Flt Control S/W**
- **Air Data**
- **Propulsion**
- **Electrical System**
- **Flt Control Actuators**
- **Altimeter**
- **Landing gear**
- **Nose wheel steering**
- **Brakes**

Mission Critical

- ***COMMs ****
- **Payloads**
- ***ECS / Fuel Mgmt ****
- ***Ground segment C^2****

**** Could be Flt Critical***

Design Redundancy In

Redundancy is obtained by:

- Minimizing single paths
- Use automatic, s/w driven switching
- Validate fail-operate by testing and demonstration
- Bench (System Center) testing of s/w prior to vehicle tests
- Vehicle ground tests
- Flight Operations / experience

DMS (Diminishing Mfg Sources) - Obsolescence

- **Architect to minimize effect**
  - **(H/W)**
    - **Stay with same processor family**
    - **Partition to accommodate fast changing technology**
  - **(S/W)**
    - **Use Higher Order Language (HOL) (e.g C++)**
    - **And Certified (DO-178B) Operating System (OS)**

      Achieve true portability / transparency
- **Provision with plenty of critical spares – e.g. processors**
- **Install an effective DMS tracking system**
- **Require OEMs to have a DMS tracking system and report changes in a timely manner**

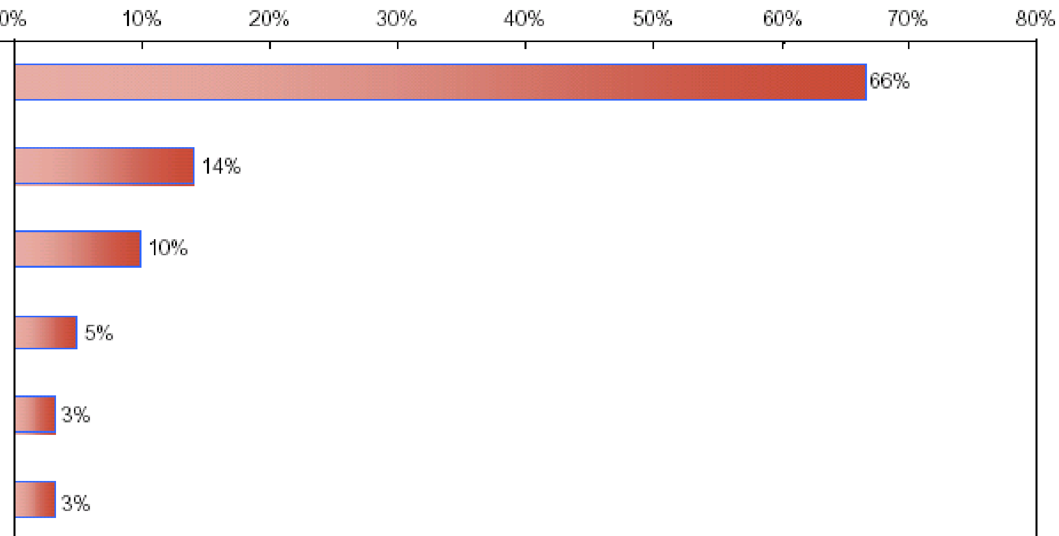
<u>LOOK AT THE ENTIRE LIFE CYCLE</u>

UAVs <u>Do</u> Have an Advantage

Accidents by Primary Cause*

Hull Loss - Worldwide Commercial Jet Fleet - 1992 through 2001

Flight Crew	98
Airplane	21
Weather	14
Maintenance	8
Misc./Other	4
Airport/ATC	4
Total with known causes	149
Unknown or awaiting reports	61
Total	210



* As determined by the investigating authority

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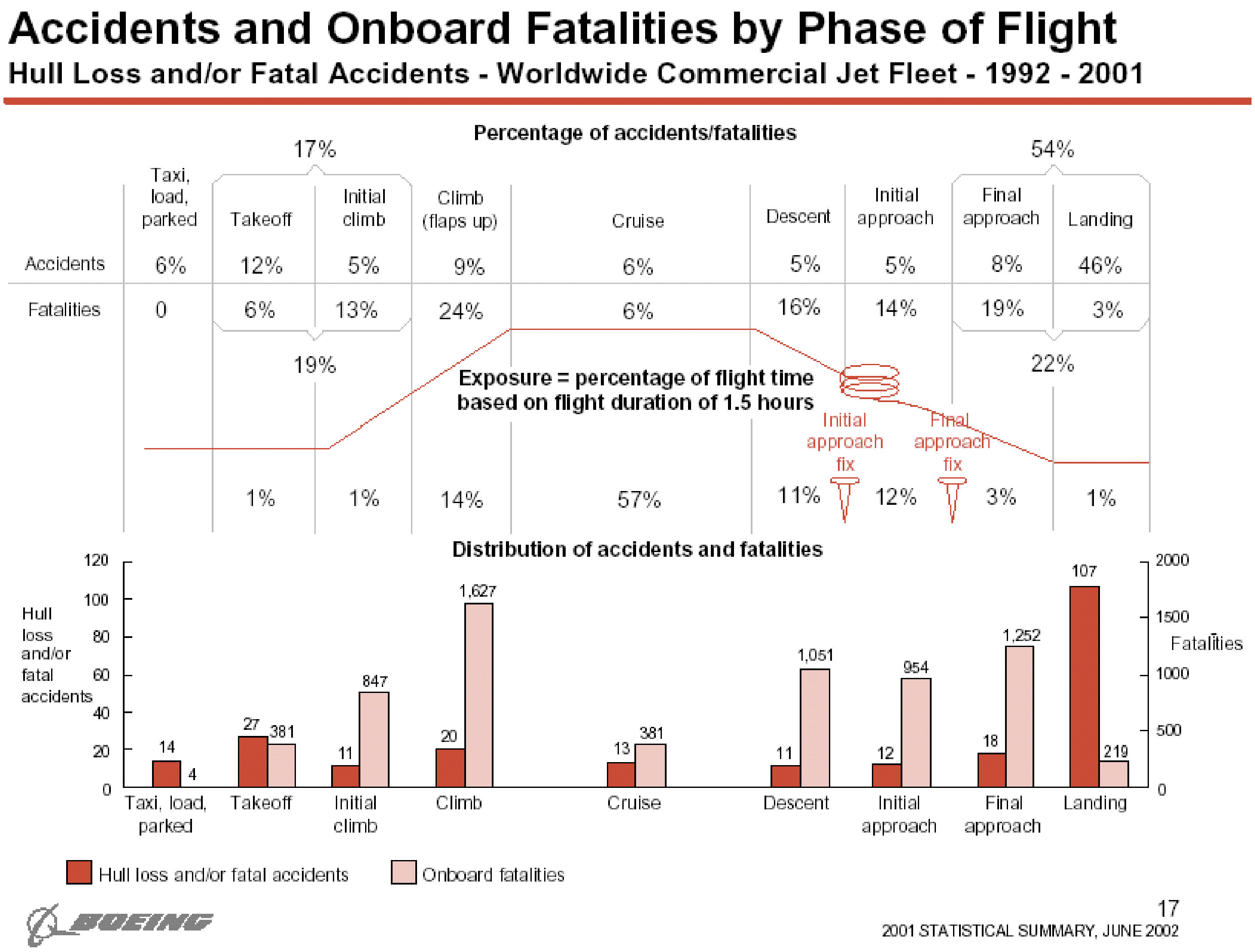
2001 STATISTICAL SUMMARY, JUNE 2002

BOEING

Learn from Others' Mistakes



UAV Major System Attributes

- **Significantly lower mission costs than manned**
- **Incorporates reliable (robust) design features**
- **Provides protection against human induced accidents through embedded flight control limits and limited override capability (outer loop <u>vs</u> inner loop)**
- **Adequate sensors to predict deterioration and failures**
- **Use of sufficient redundancy to provide fail-operate systems**
- **Self "healing" and self controlling systems operation**
- **Tolerate wide environmental ranges, as operations are generally in hostile and/or unknown environments (pressures, temperatures, turbulent atmospheres, etc.)**
- **Operate in civilian airspace (with or without waivers) over friendly as well as hostile countries.**

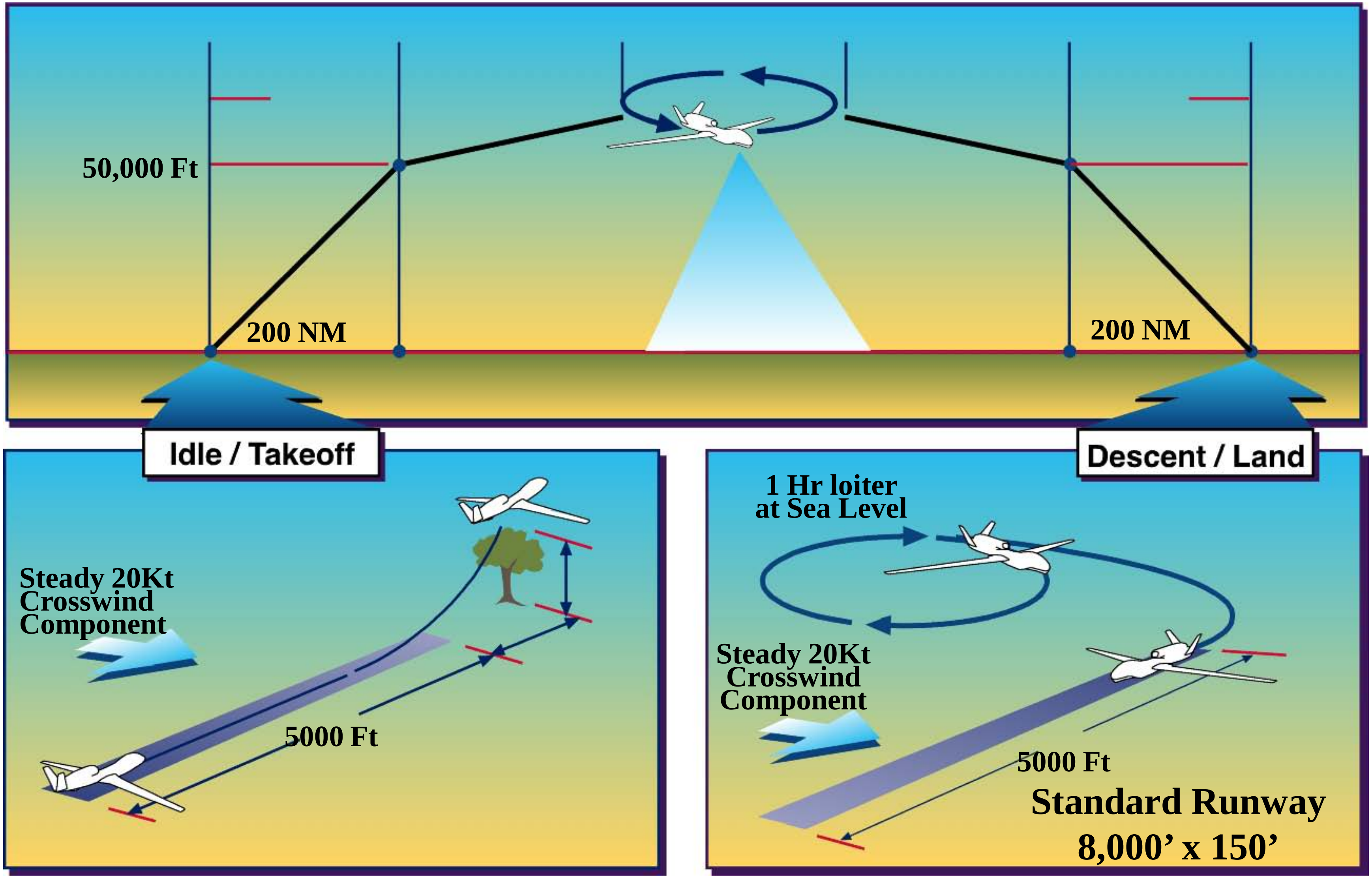
Design Requirements

Original System - Goals / Requirement

PROGRAM GOALS	CHARACTERISTICS
14,000 NMI	**Maximum Range**
65,000 FT+	**Maximum Altitude**
42 Hrs	**Maximum Endurance**
1.5 - 50 Mbps	**SATCOM Datalink**
> 50 Mbps	**LOS Datalink**
1.0/0.3m resolution (WAS/Spot)	**SAR**
20 - 200Km/10m Range resolution	**MTI**
EO NIIRS 6.5/6.0 (Spot/WAS)	**EO**
IR NIIRS 5.5/5.0 (Spot/WAS)	**IR**
40,000 Sq. NMI/Day	**Wide Area Search**
1,900 Spots Targets /Day	**Target Coverage**
< 20 meter CEP	**Location Accuracy**

Just 1 Requirement - Unit Flyaway Price

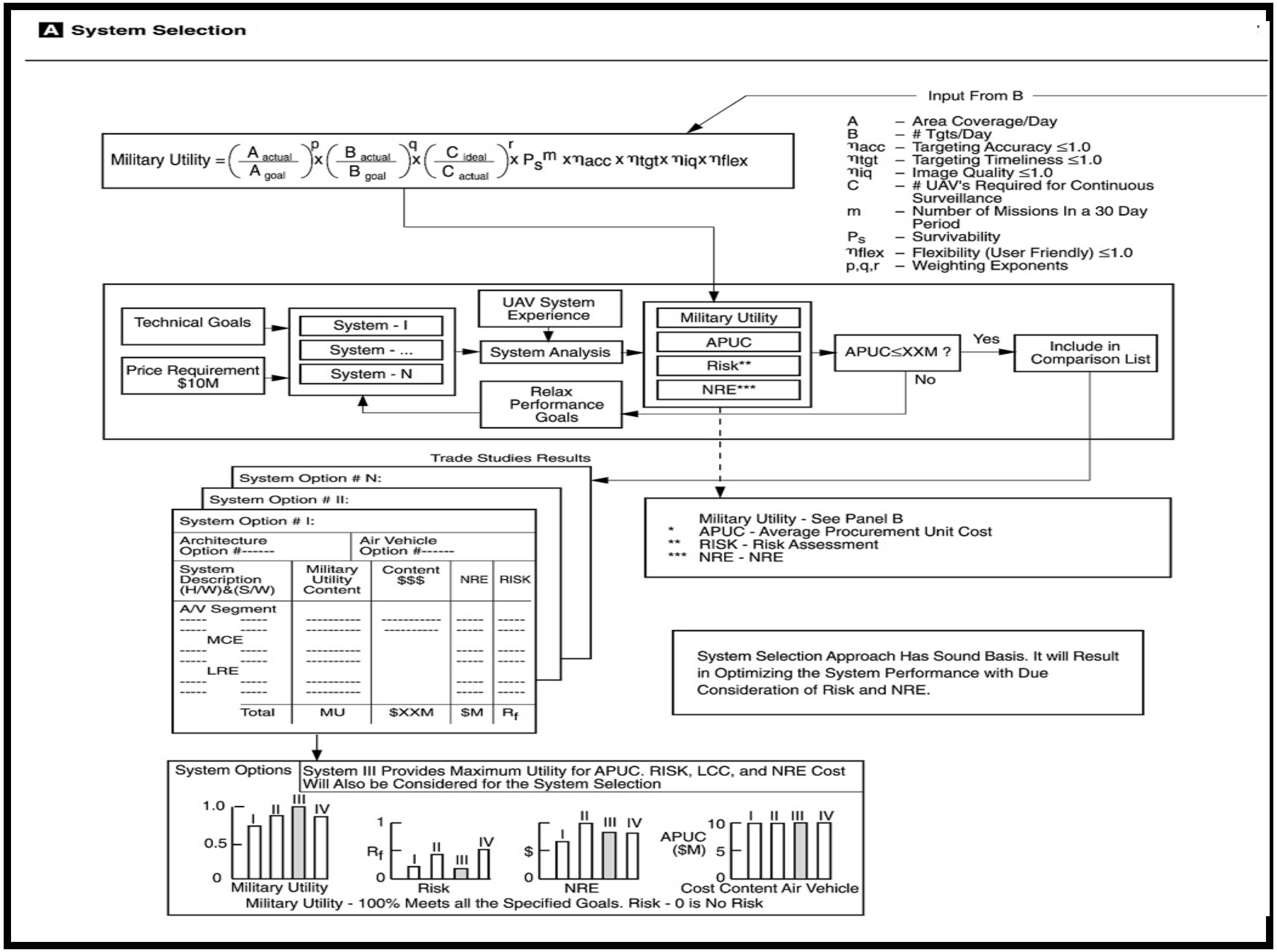
Notional Mission Profile



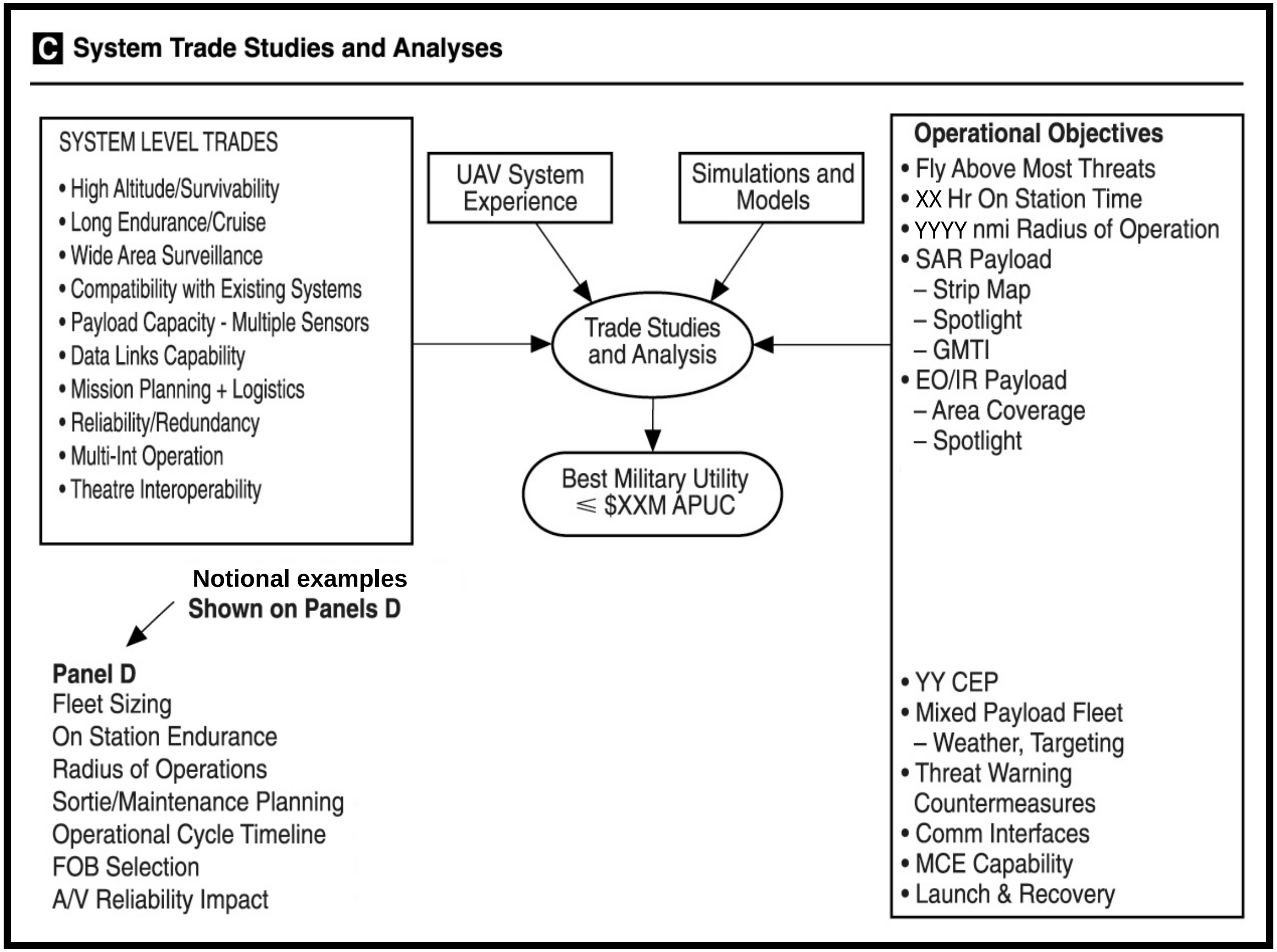
System Selection Process

- A disciplined systems approach was used to define the overall system:
  - Analysis
  - Trades
  - Sizing and Sortie profiles
  - Survivability issues considered
  - Mission radius of operations reviewed

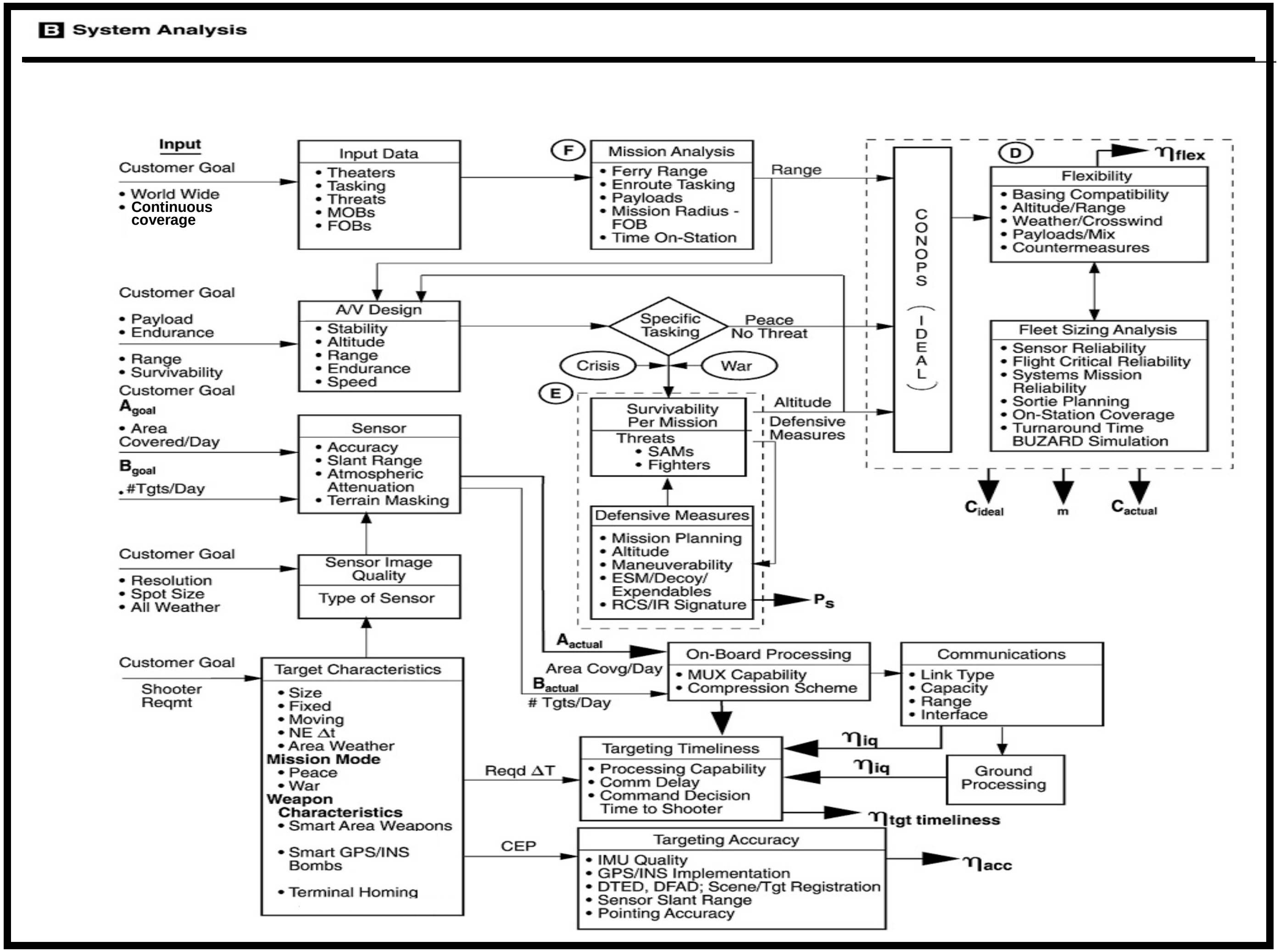
System Selection



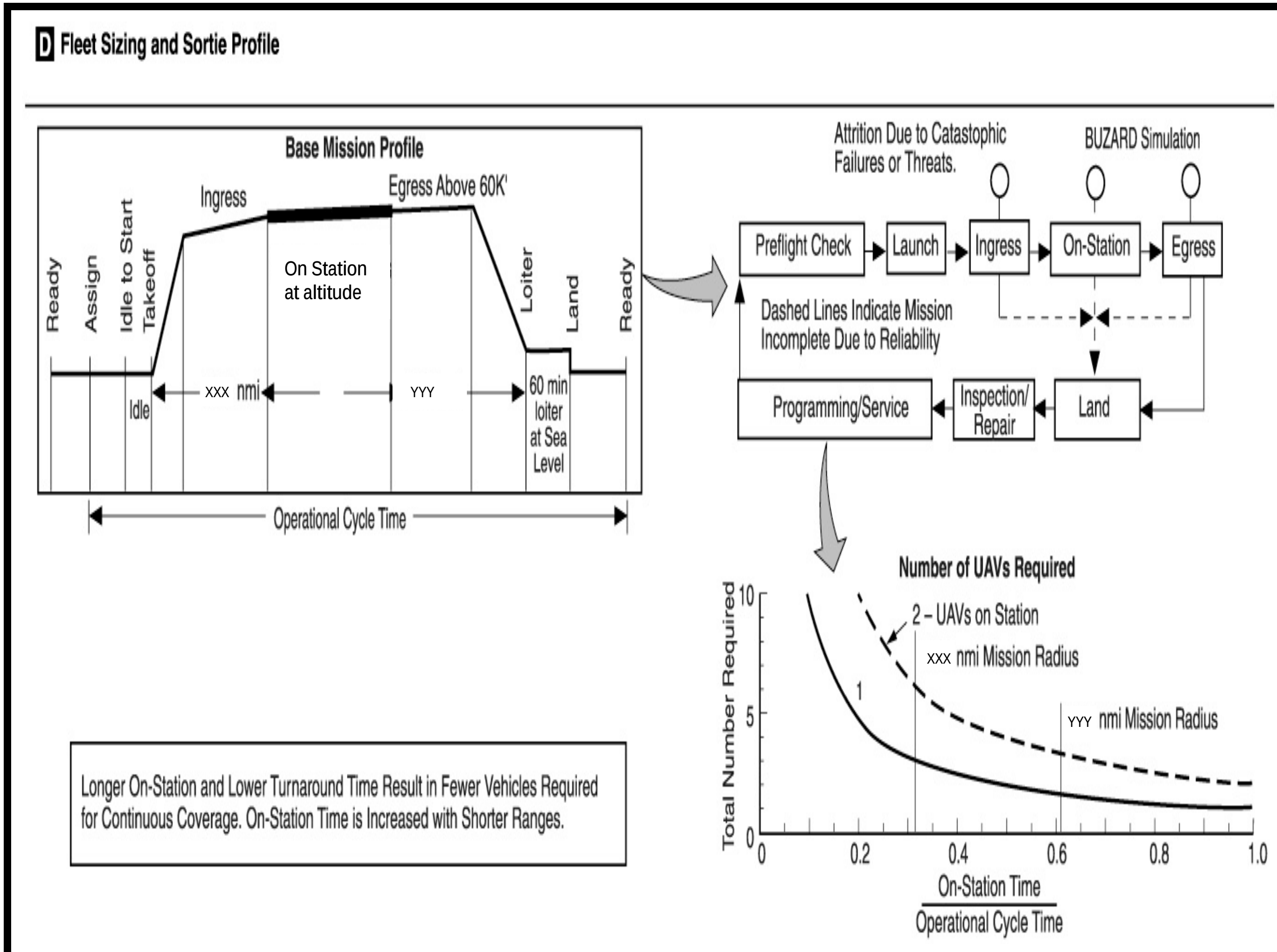
Trades and Analyses



Analysis Approach



Sizing and Sortie Profile

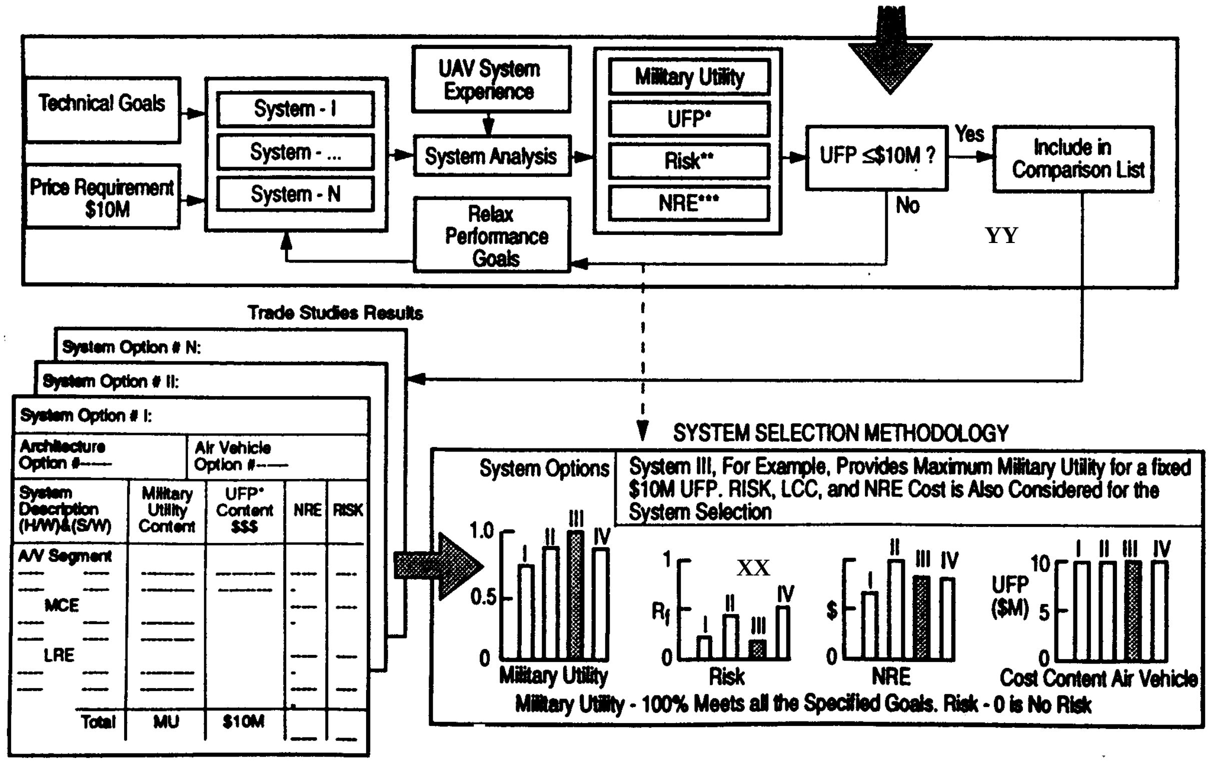


Original Design Objective

Balance Military Utility (MU) and Risk within Unit Flyaway Price (UFP)

MU UFP 1 Loss / XXX Missions Availability
Reliability = YYY Ao = 0.90

Risks
Schedule
Technical
Costs



Typical ISR UAV Cost Breakdown

	UFP Breakdown	
Description	**Cost Basis**	**%UFP**
	General Equipment	
Airframe		
Structures	Estimate	22.74
Landing Gear	Bid	1.65
Control Surf Actuation	Bid	0.68
Propulsion	Bid	16.31
Fuel System	Estimate	0.75
Electrical Sys	Estimate	1.66
Environ Ctl Sys	Bid	1.02
Hydraulics	Estimate	1.81
Payload		
SAR/GMTI	Bid	23.29
Self Defense	Quotation	3.22
Data Recording	Quotation	0.78
Payload Mgt	Quotation	0.56
Communications	Bid	14.46
ESM	Quotation	2.89
Avionics		
Avionics	Estimate	3.49
	Mission Specific Equipment	
EO/IR	Bid	4.61

The HALE vehicle - (High Altitude Long Endurance)

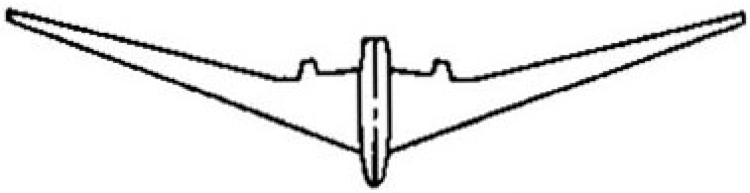
In Oct '94 Teledyne-Ryan was one of five remaining competing companies for the Tier II+, a contract to be awarded for a vehicle that could fly very high and remain on station for very long periods of time.

Its mission was to fly at 65,000 feet (mostly out of harms way), and remain aloft for 40 hours, carrying three high quality sensors, an EO, an IR camera as well as a Synthetic Aperture Radar (SAR) imaging sensor.

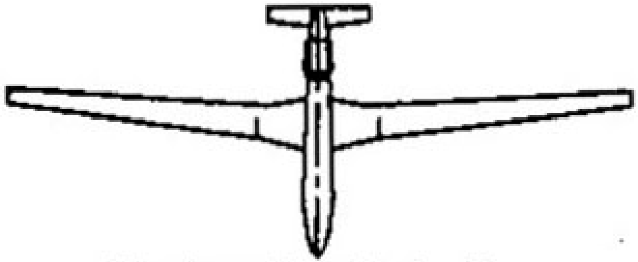
During the first phase of this competition each company team conducted their preliminary design and made a proposal to the DoD's Advanced Research Projects Agency, acting as agent for the Defense Airborne Reconnaissance Office.

Three Design Approaches Explored

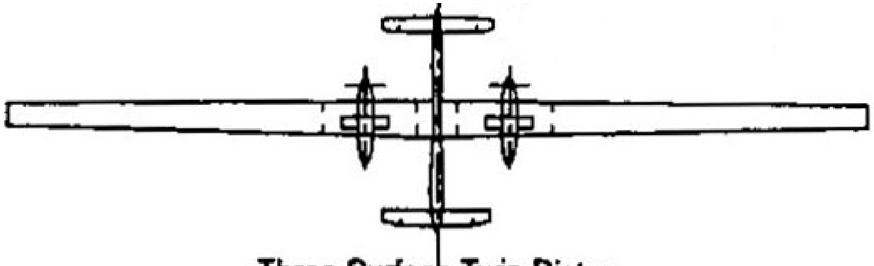
High Wing Loading Turbofan	Low Wing Loading Turbofan	Low Wing Loading Turbocharged Recip.
Span 116 Ft	Span 150 Ft	Span 200 Ft



Single or Twin Turbo Fan Powered Flying Wing

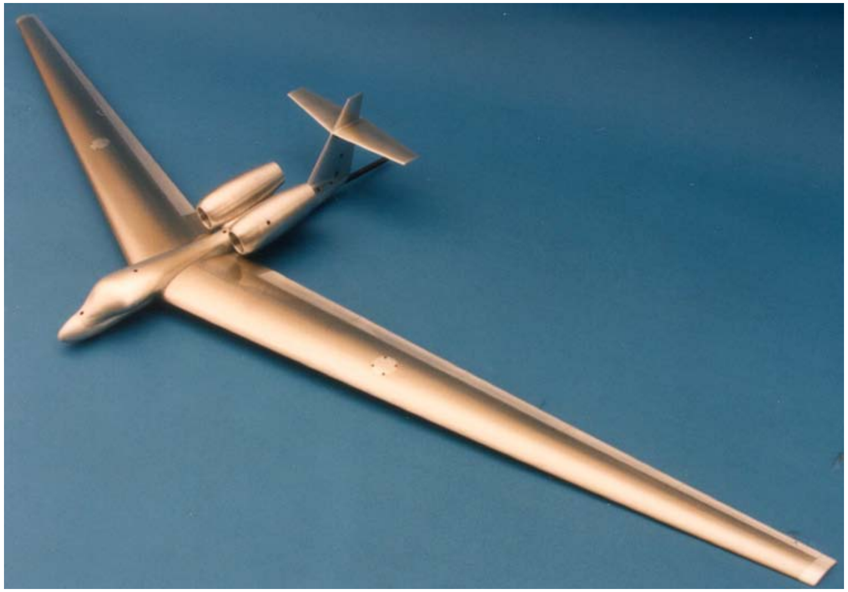


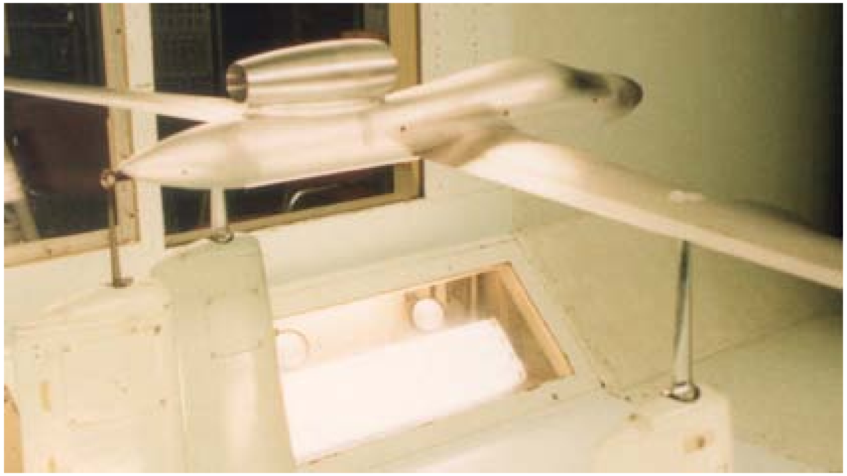
Single or Twin Turbo Fan Powered Conventional Design



Three Surface Twin Piston Engine / Propeller Design

Configuration Development





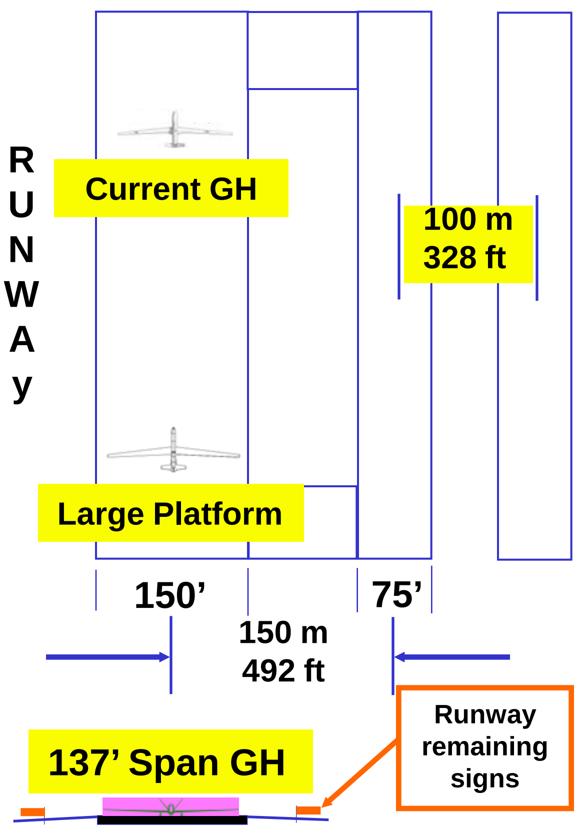
Runway Considerations

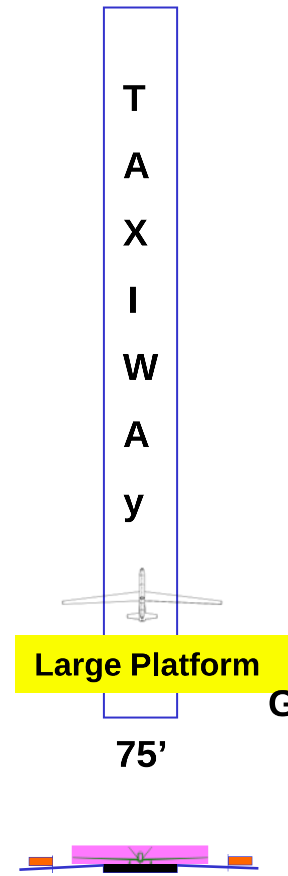
Reference 1:

UFC 3-260-01 Airfield and Heliport Planning and Design, AFJMAN 32-1076, and FAA Circular AC 15015345144F

Reference 2:

NATO Approved Criteria and Standards for Airfields. 1999, BI-MNCD 85-5





Shown:

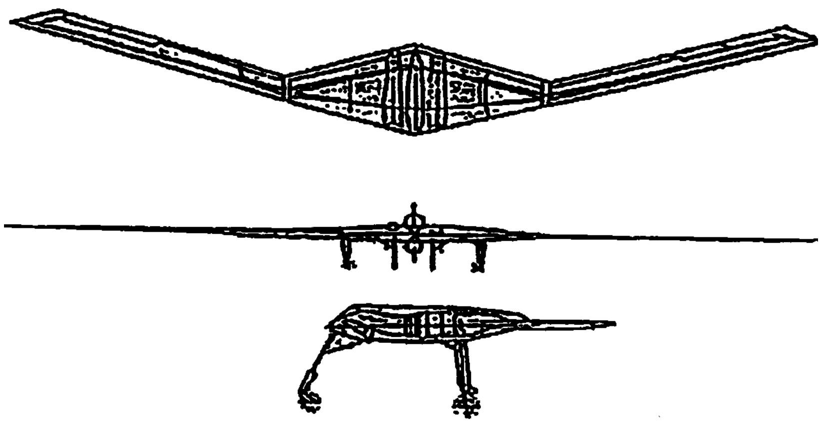
NATO Runway; Std field 8000' x 150'

GH/U-2 MOB 12,000' x 300'

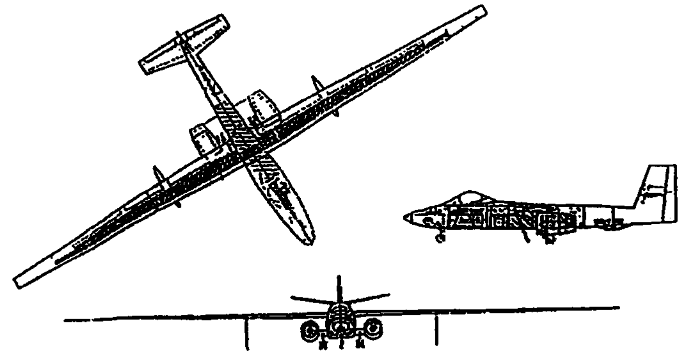
Taxiway; Std 75'

Tier II+ Competition

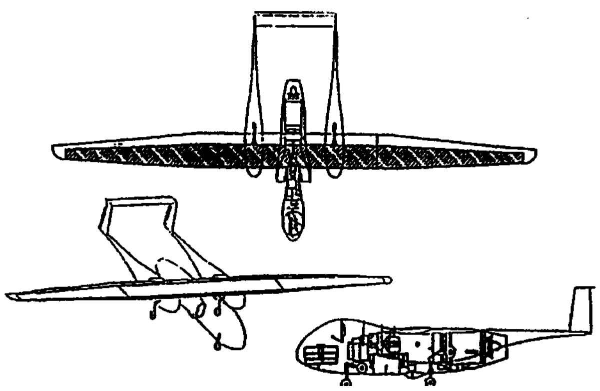
Aka the 1995 Paris Fashion Show



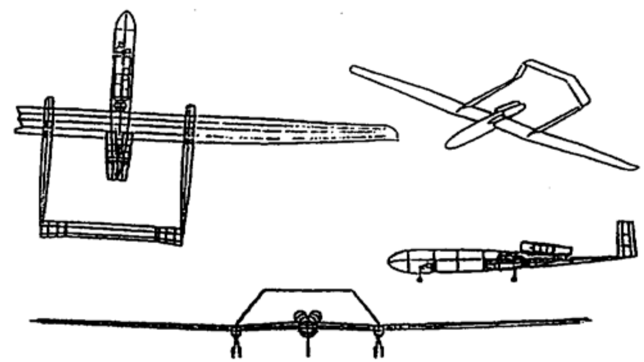
Loral Systems, San Jose, CA



Northrop Grumman, Melbourne, FL



Lockheed Advanced Development Co.



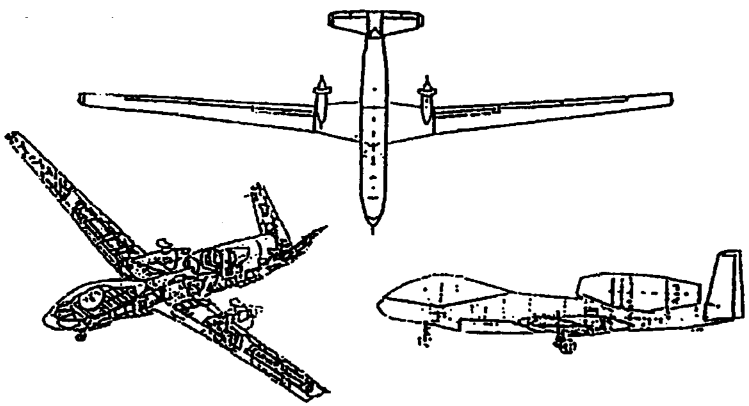
Orbital Sciences Corp., Dulles, VA

All Shown at the Same Scale

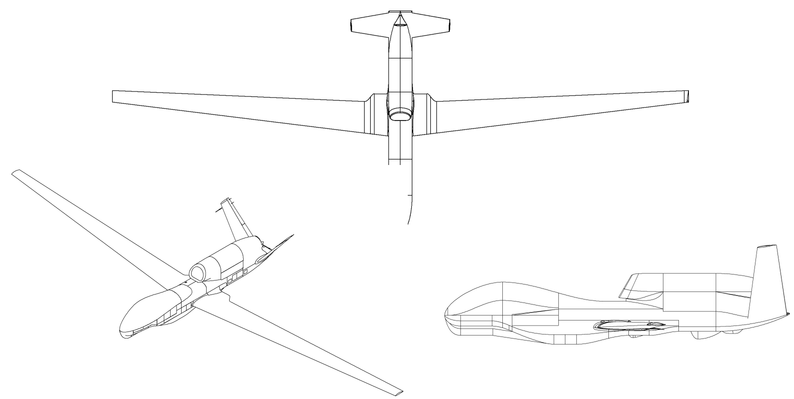
And Like in Paris, All Designed to the Same Requirements !

The Global Hawk

In 1995 the San Diego based team of Teledyne Ryan was awarded the contract and the Tier II Plus - (Global Hawk) was born.

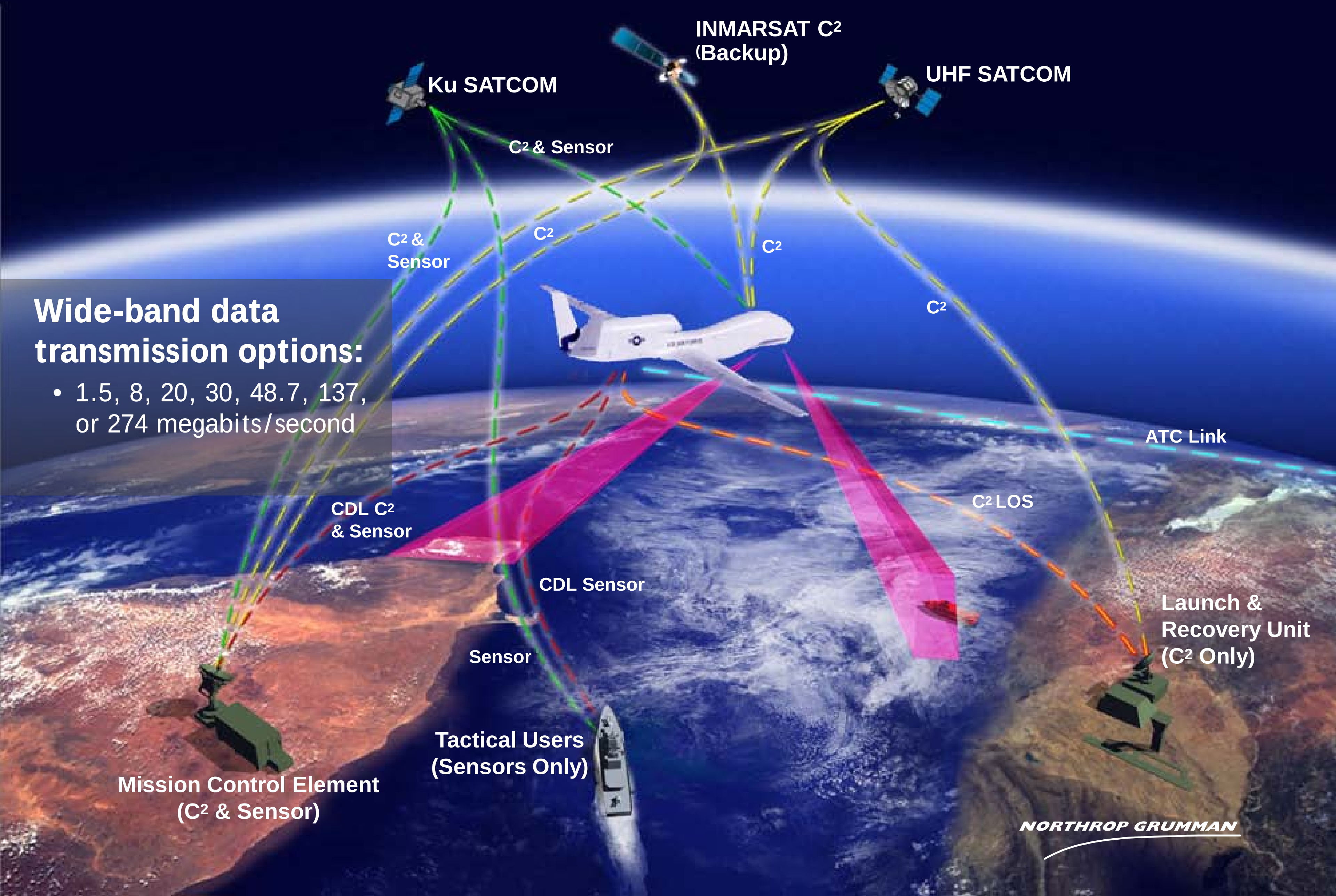


Teledyne Ryan Aeronautical



Then . . . . and Now

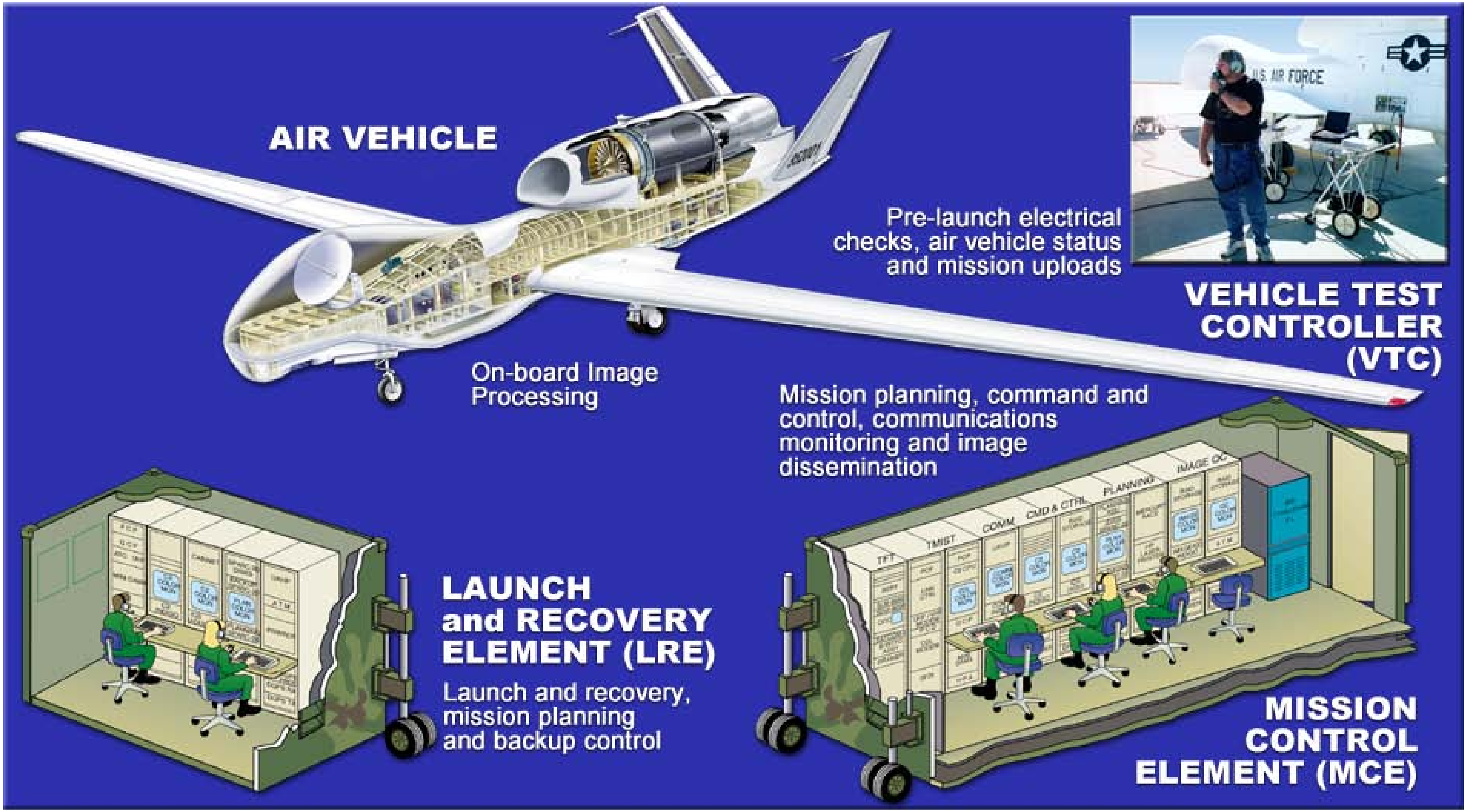
System Overview



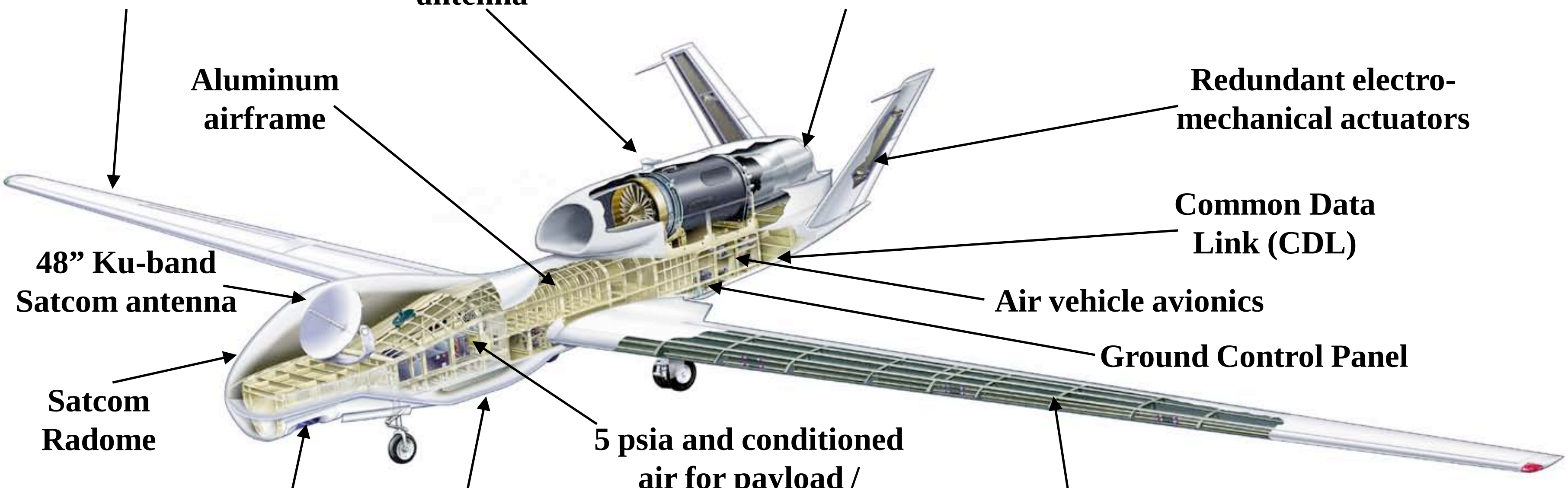
Wide-band data transmission options:

- 1.5, 8, 20, 30, 48.7, 137, or 274 megabits/second

System Elements

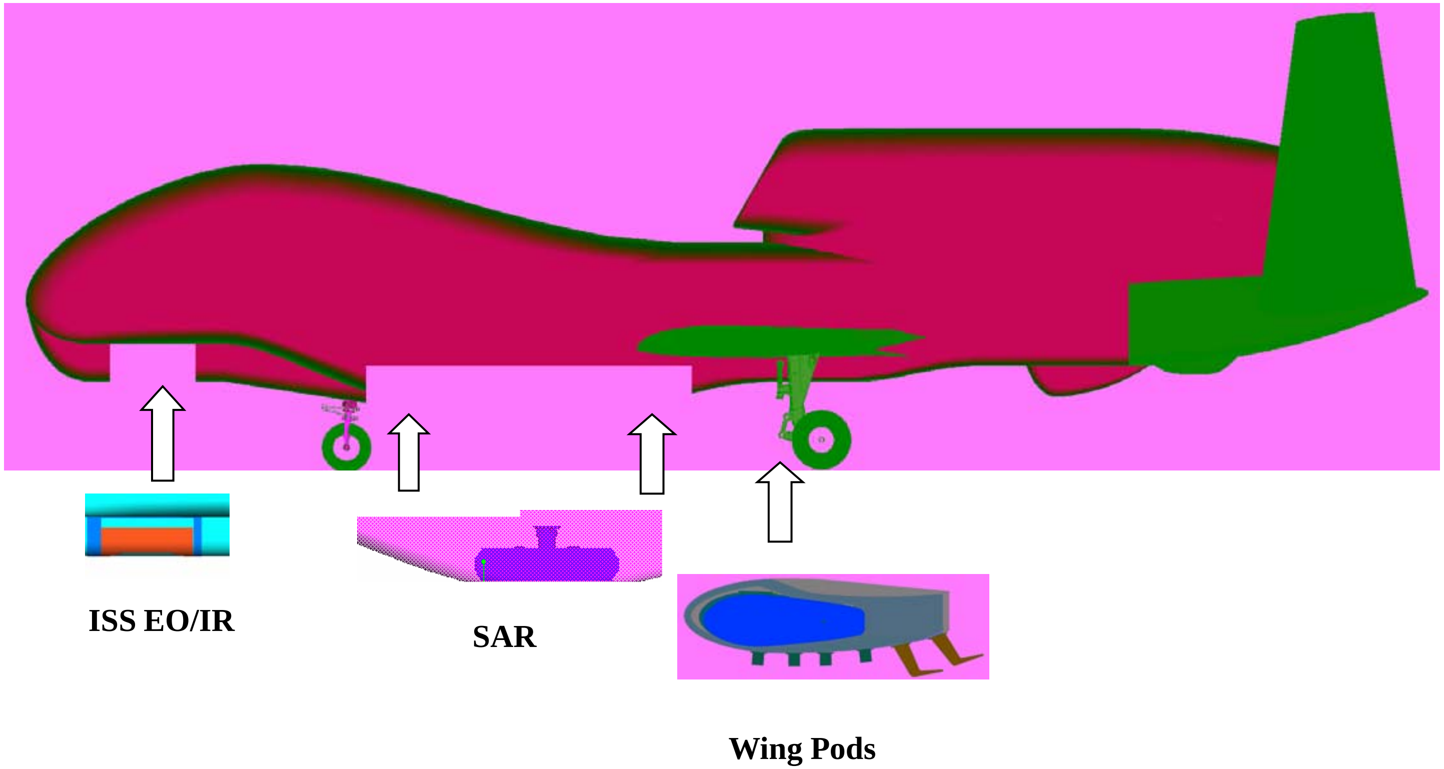


Northrop Grumman-RQ-4A
(Tier II+ Air Vehicle)

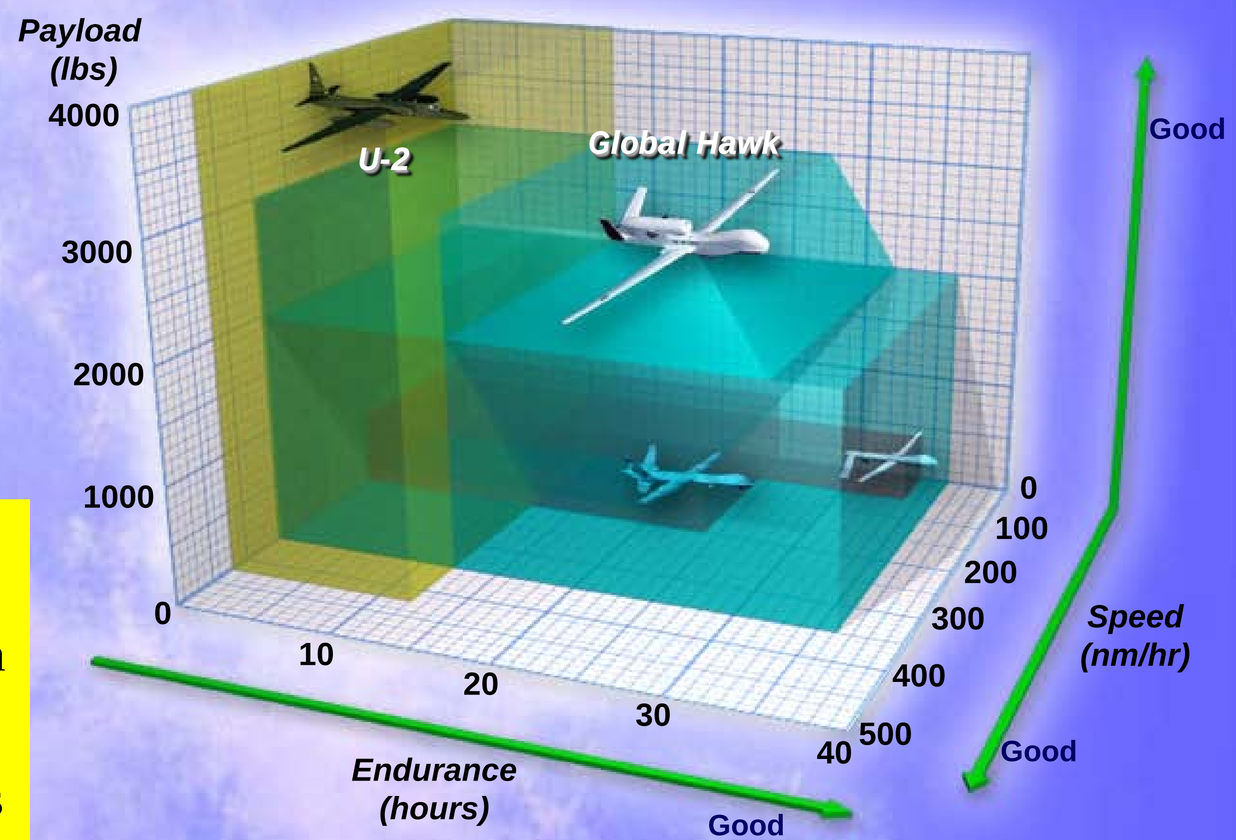


Wing span - 116 feet
Takeoff Wt - 25,600 lbs
Payload - 2,000 lbs
Endurance - 31.5 hrs

ACTD Modularity - Original Design



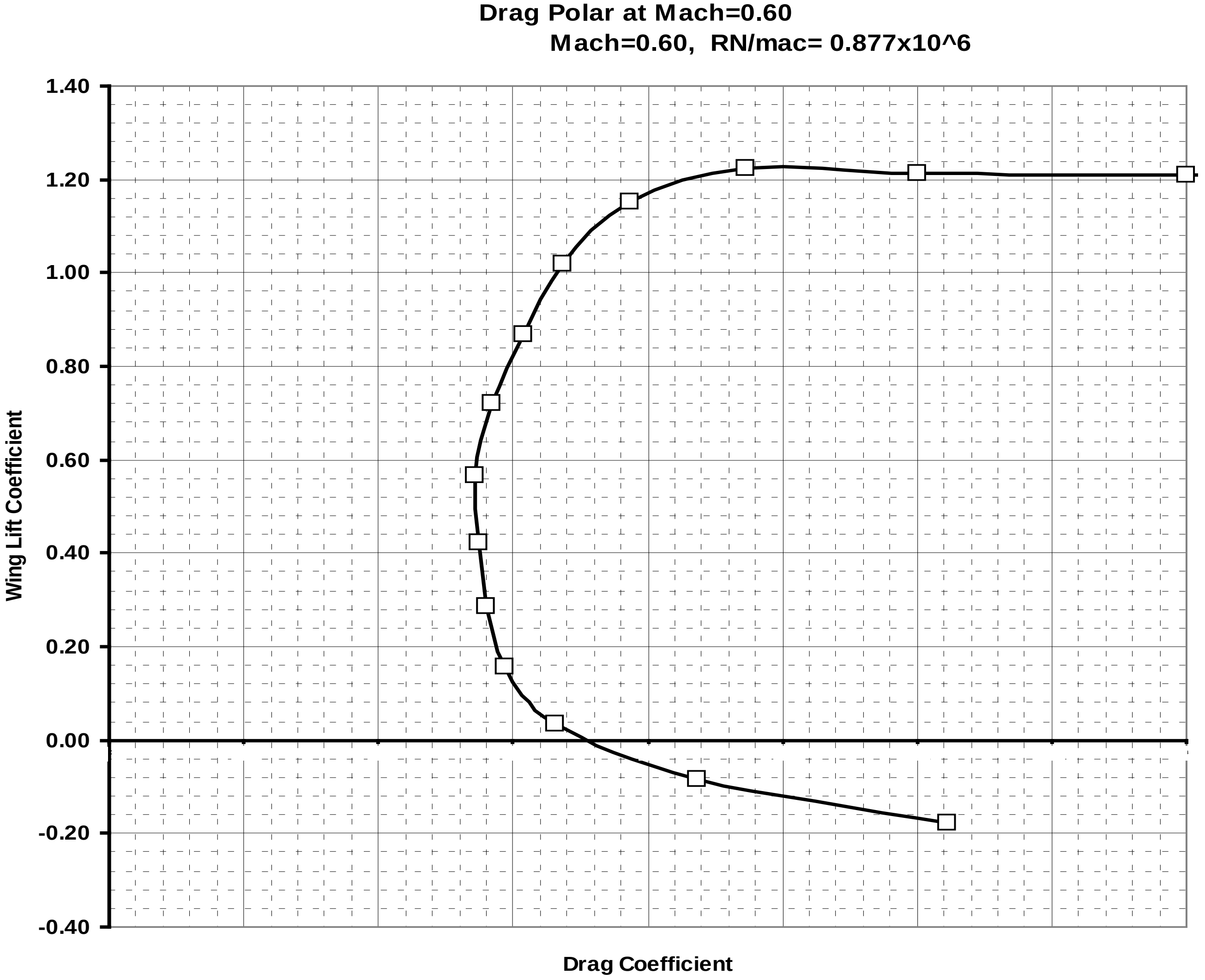
Design Performance



Persistence and payload - large drivers in assessing true mission performance / system capability.

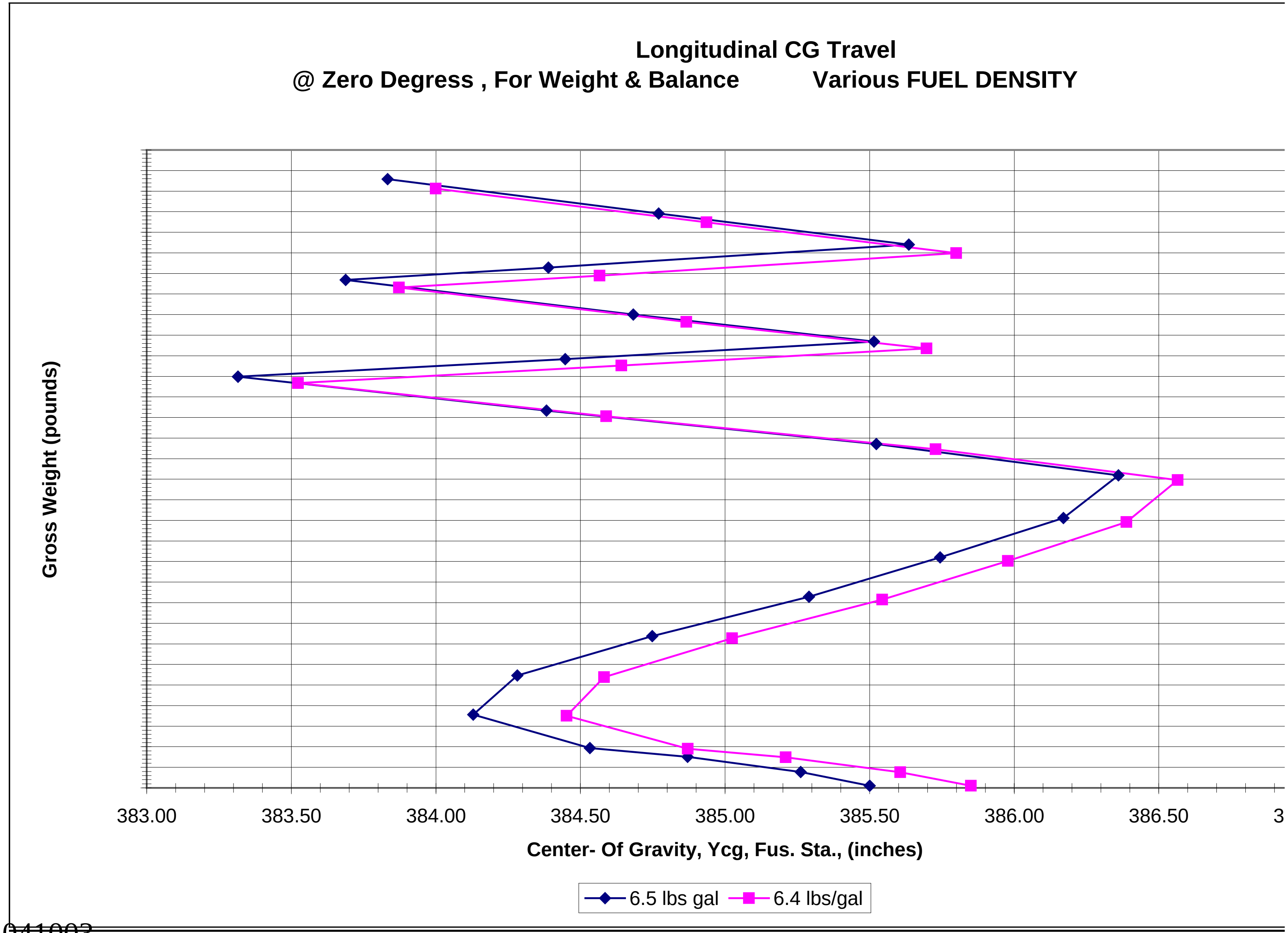
Speed - supports warfighter's time to area of interest.

Drag Polar



Drag Polar at Mach=0.60
Mach=0.60, RN/mac= 0.877x10^6
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
Wing Lift Coefficient
Drag Coefficient

CG Travel vs Body Angle with Fuel Burn

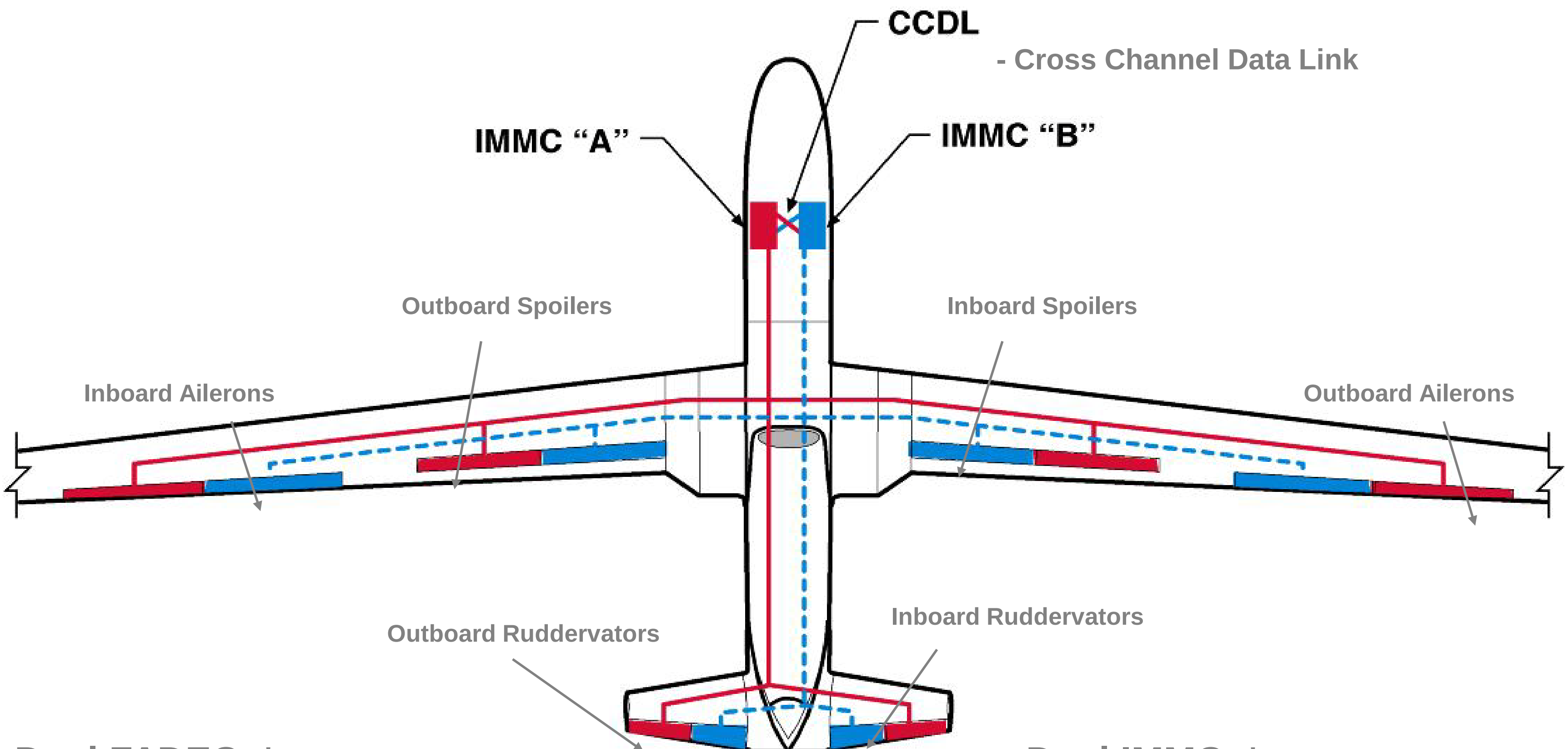


Design Implementation

&

Design Specifics

Redundancy Implementation



Dual FADECs*

Dual Air Data Systems

Dual Dissimilar Navigation Systems

FADEC - Full Authority Digital Engine Control

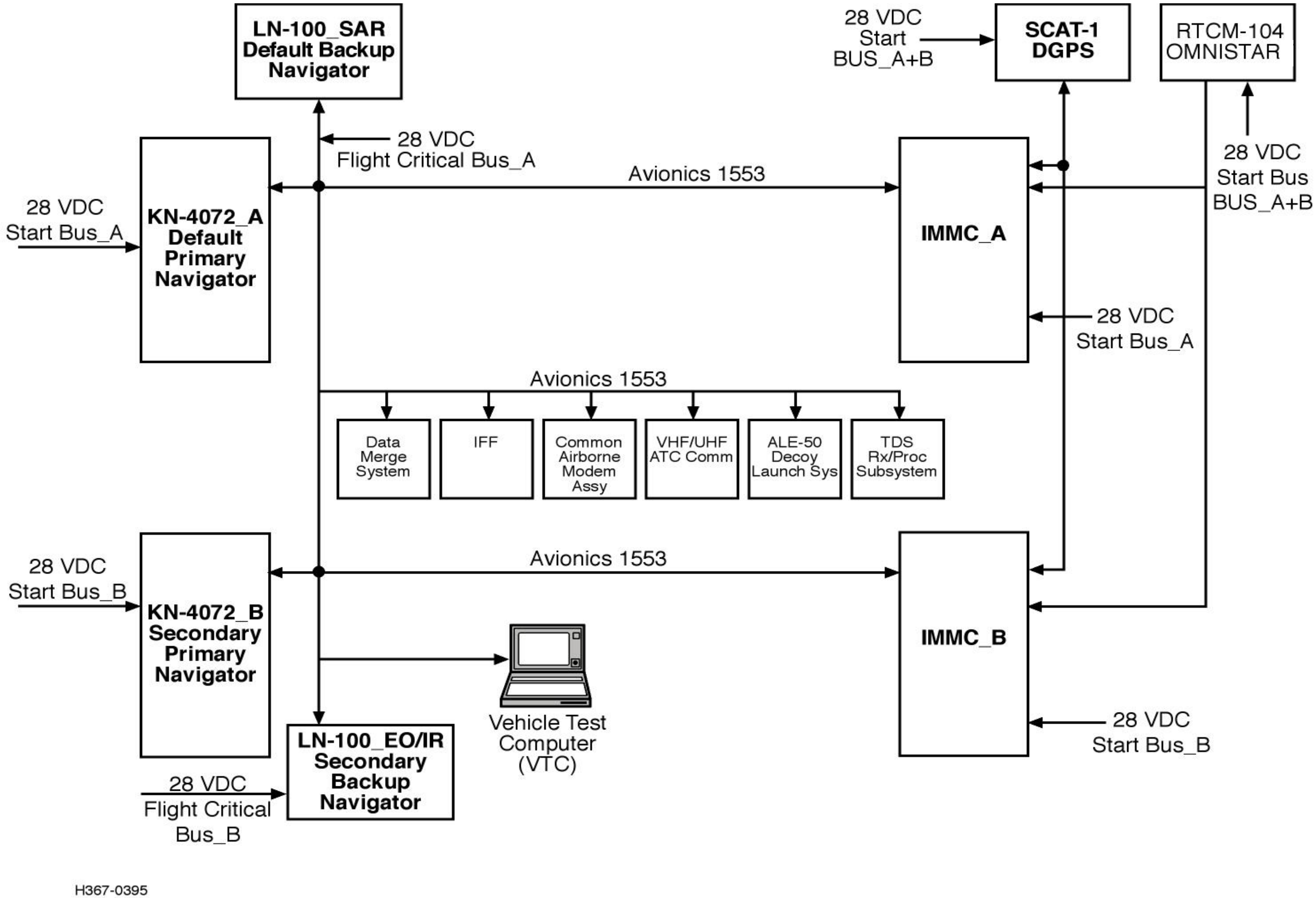
Dual IMMCs*

Dual Flight Critical Buses

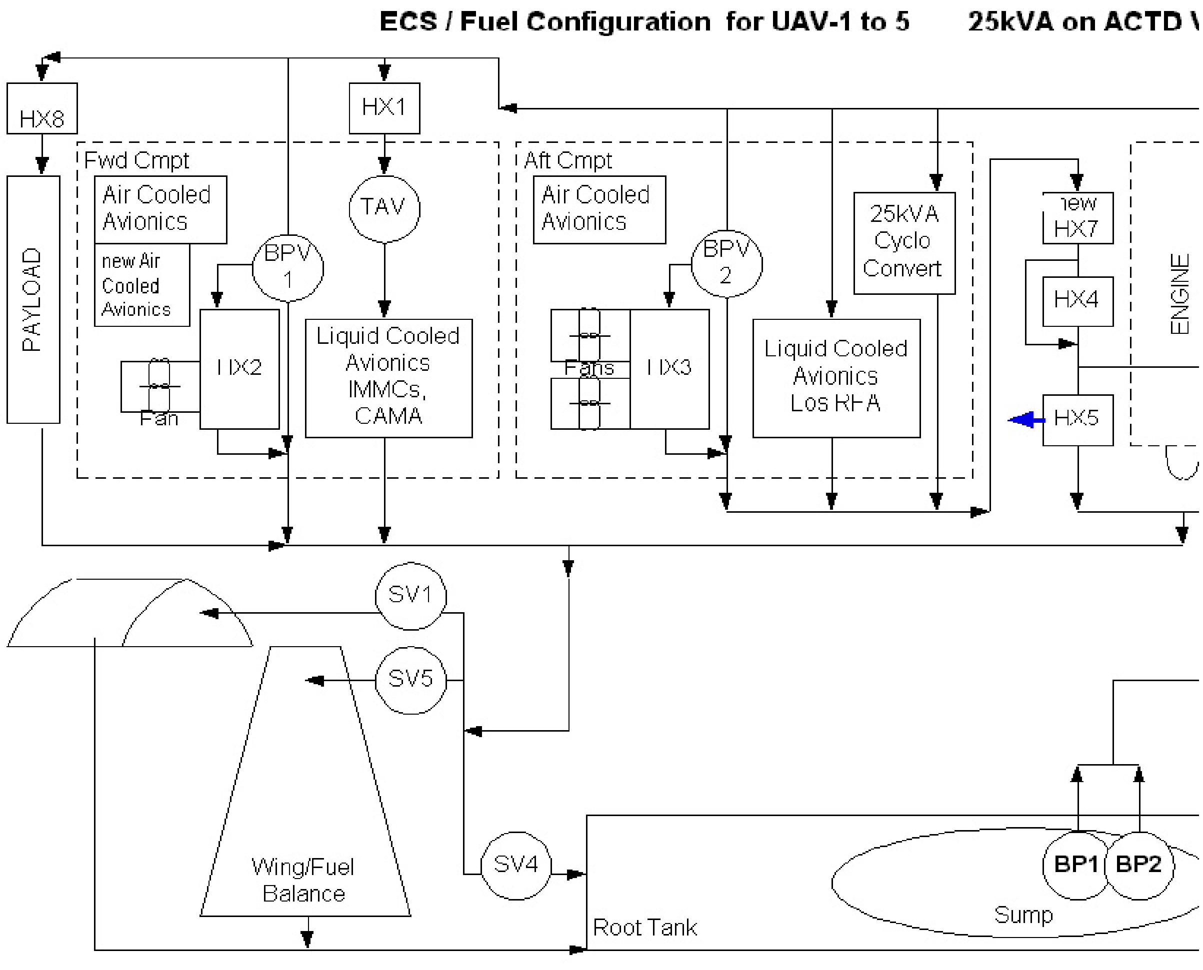
Dual Power Buses

IMMC- Integrated Mission Management Computer

Navigation & Guidance Schematic



Fuel / ECS Functional Block Diagram



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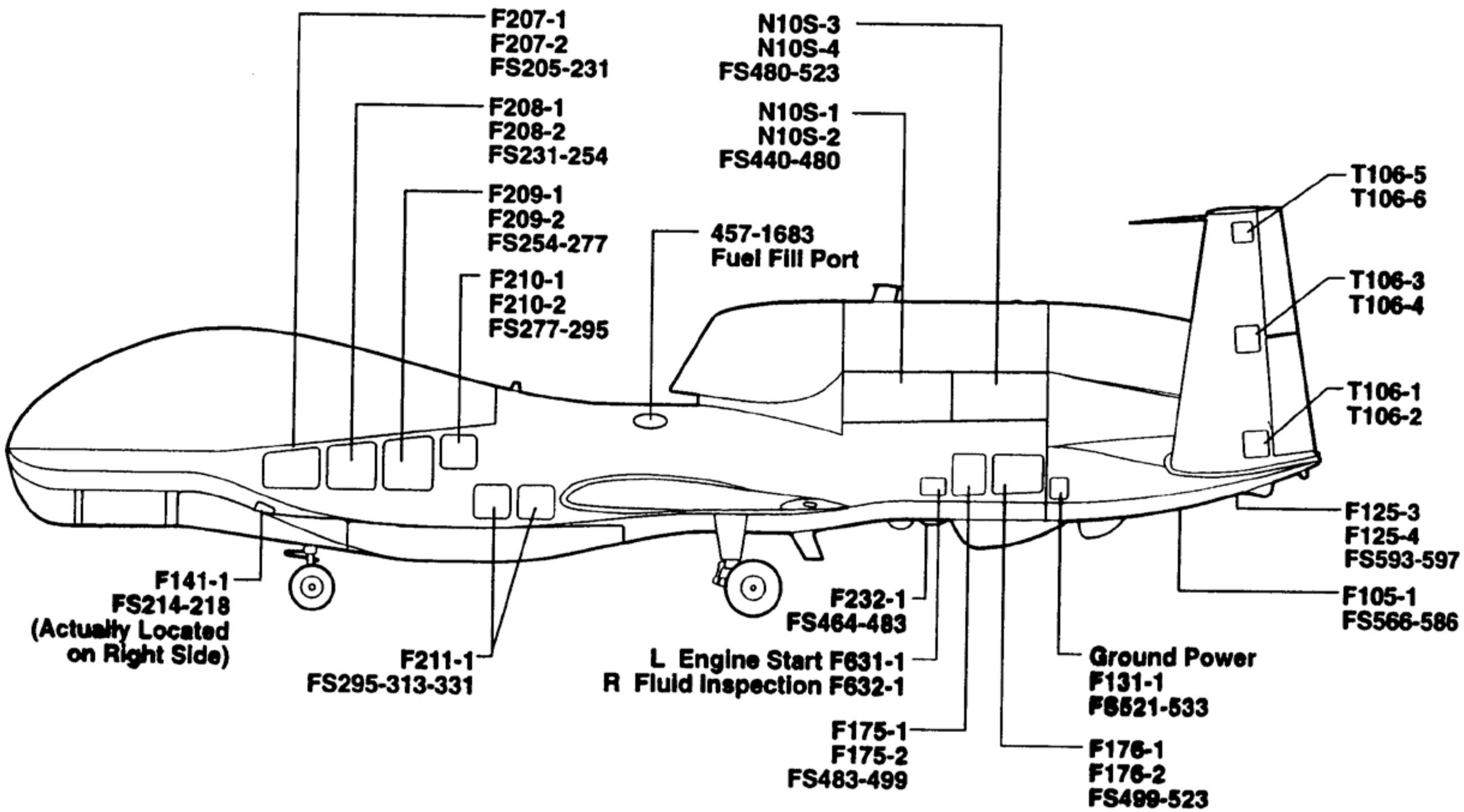
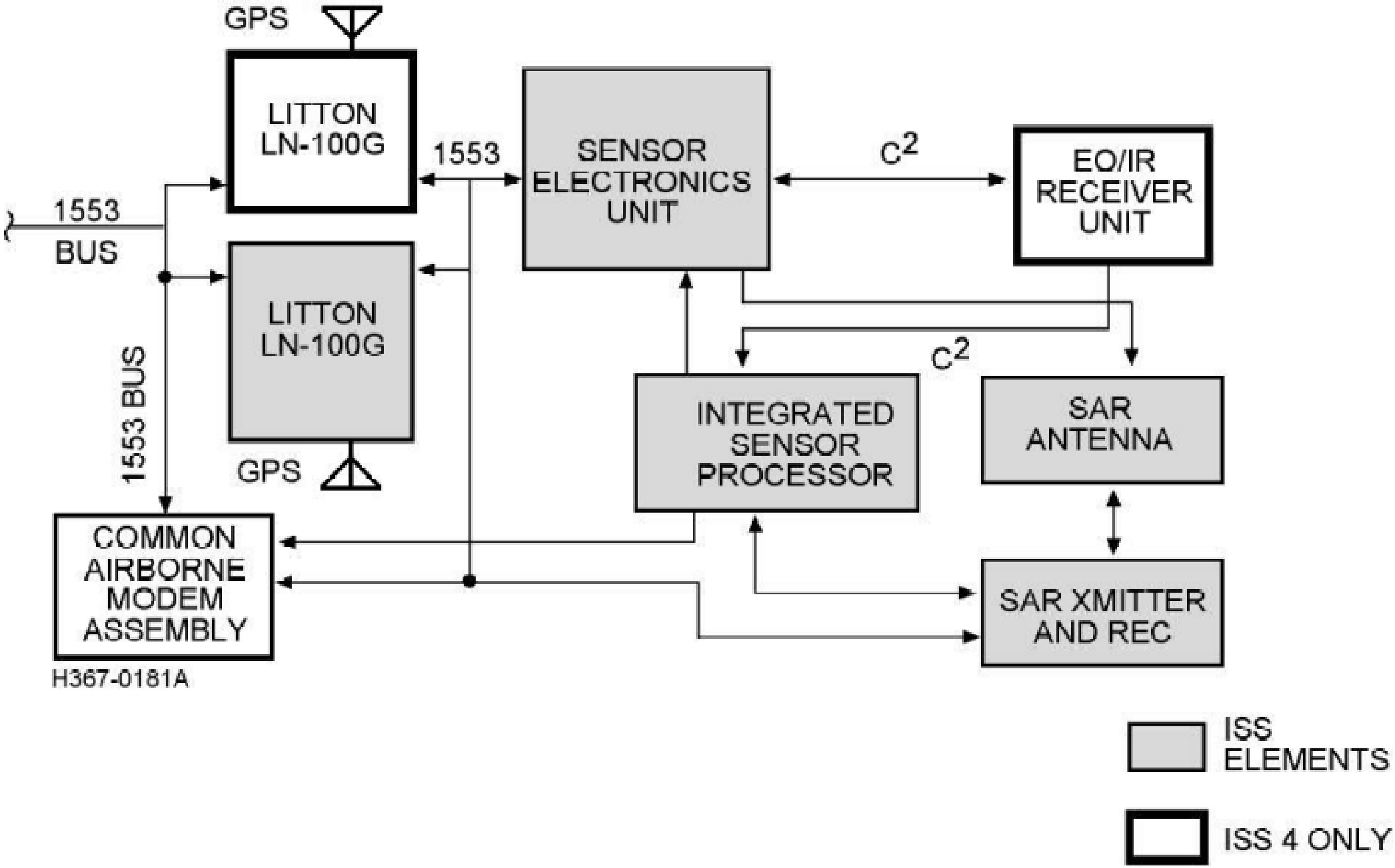
Maintainability / Accessibility

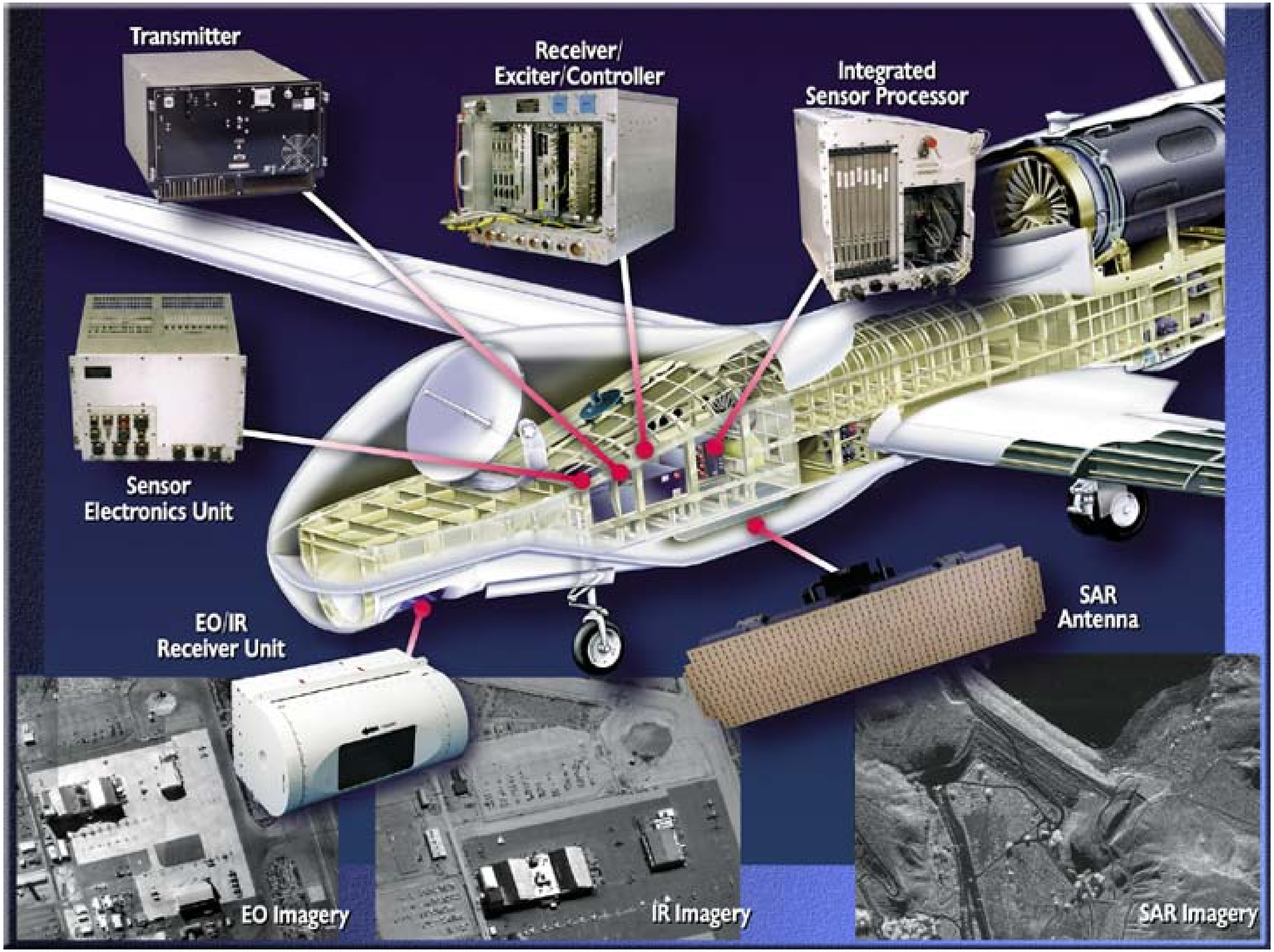
Access Door Location / Identification



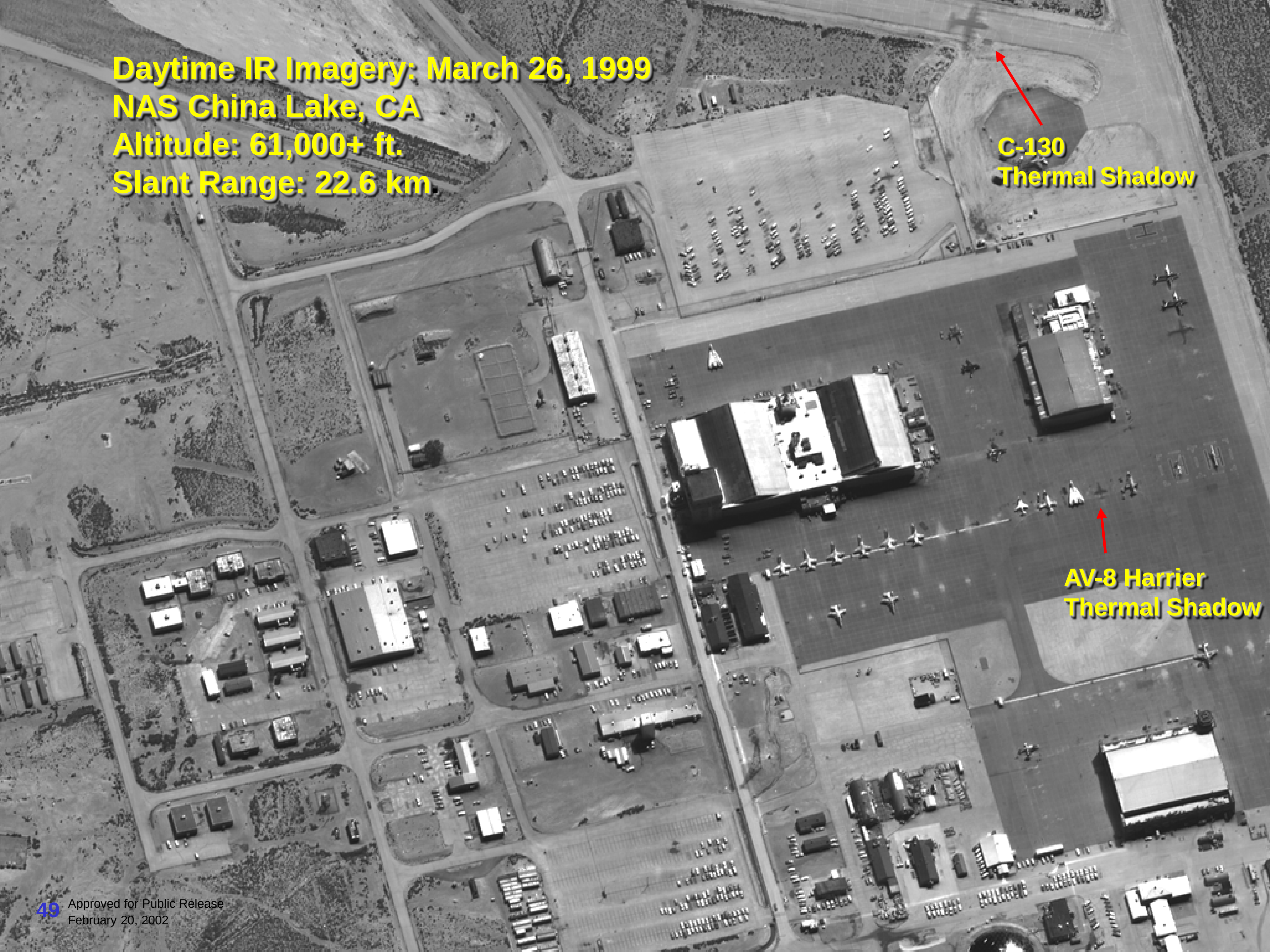
Sensor Block Diagram



Integrated Sensor Suite



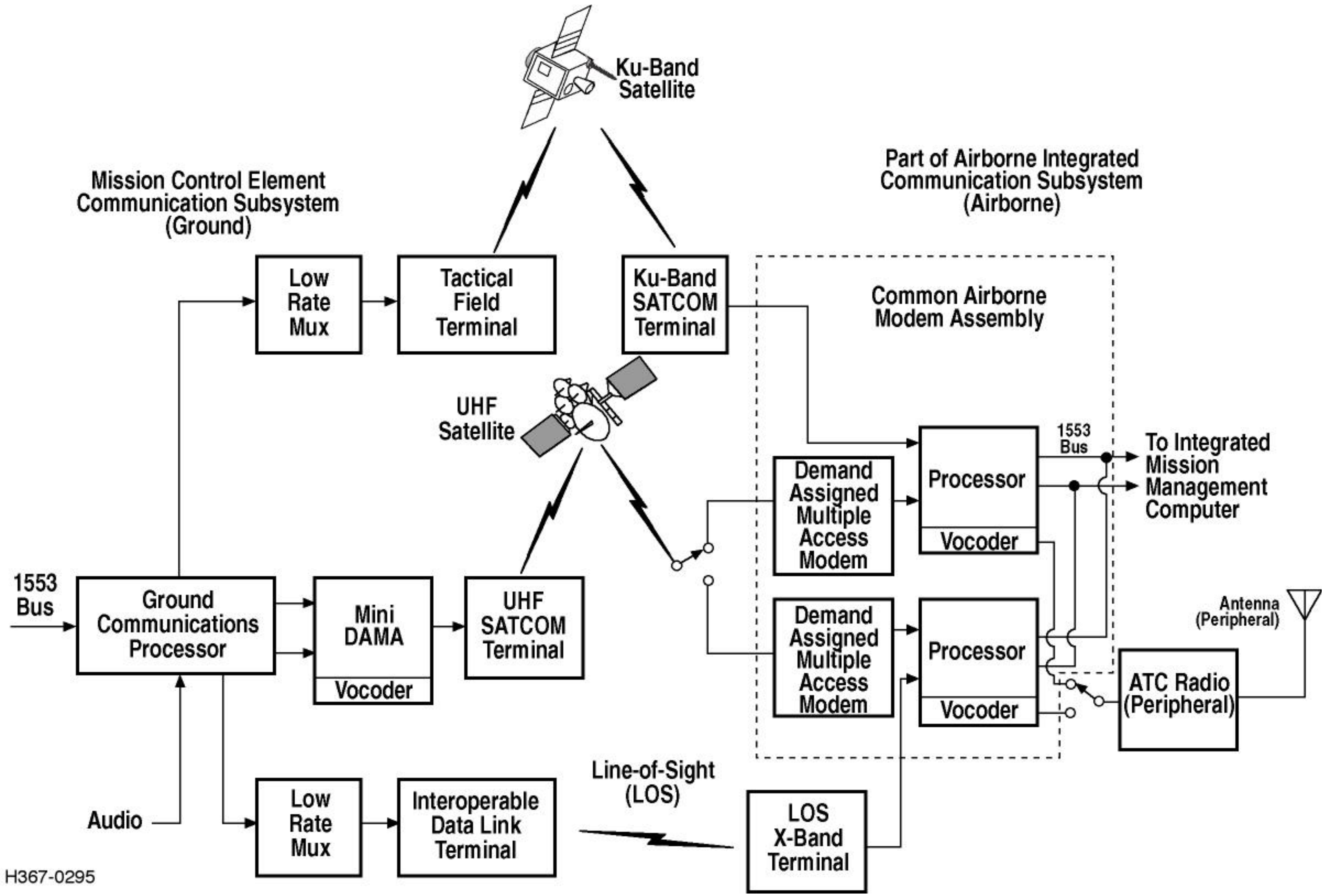

EO Imagery: January 16, 2001
Edwards Air Force Base, CA
Altitude: 60,000+ ft.
Slant Range: 33 km.


Daytime IR Imagery: March 26, 1999
NAS China Lake, CA
Altitude: 61,000+ ft.
Slant Range: 22.6 km.
C-130
Thermal Shadow
AV-8 Harrier
Thermal Shadow

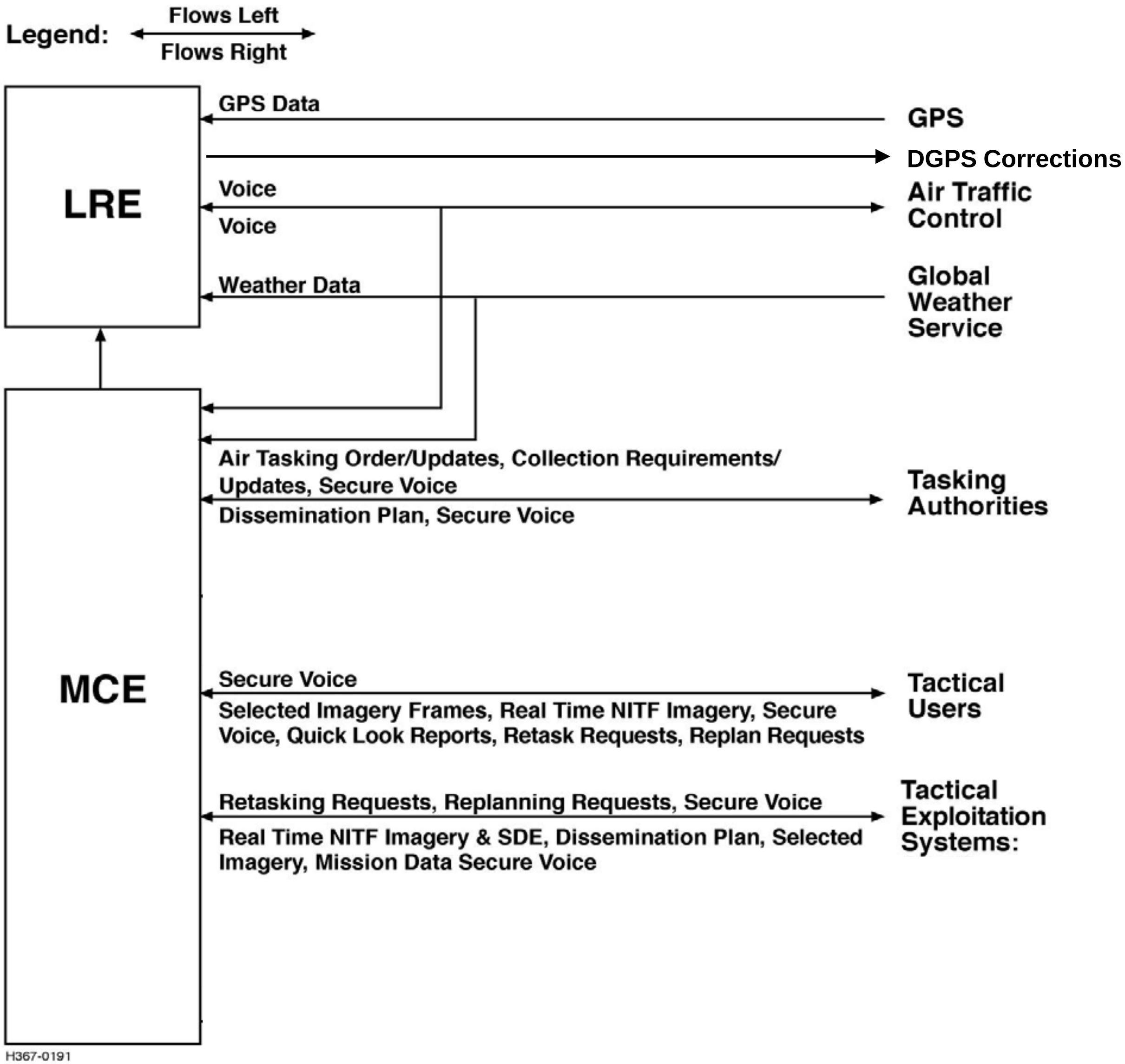

SAR Imagery: February 20, 1999
Lake Success Dam, CA
Altitude: 62,000+ ft.
Slant Range: 86.3 km.

Global Hawk Airborne Integrated Communication Subsystem

MCE Communications Schematic



Air Vehicle-to-Ground Stations Interfaces



An MCE at Suffolk, VA

All-Encompassing System Development & Verification Environment is a Must

Global Hawk is not a UAV. Global Hawk is a **SYSTEM**. In order to develop and test this system, a Systems Center provides the following capabilities to ensure total system verification before each flight event.

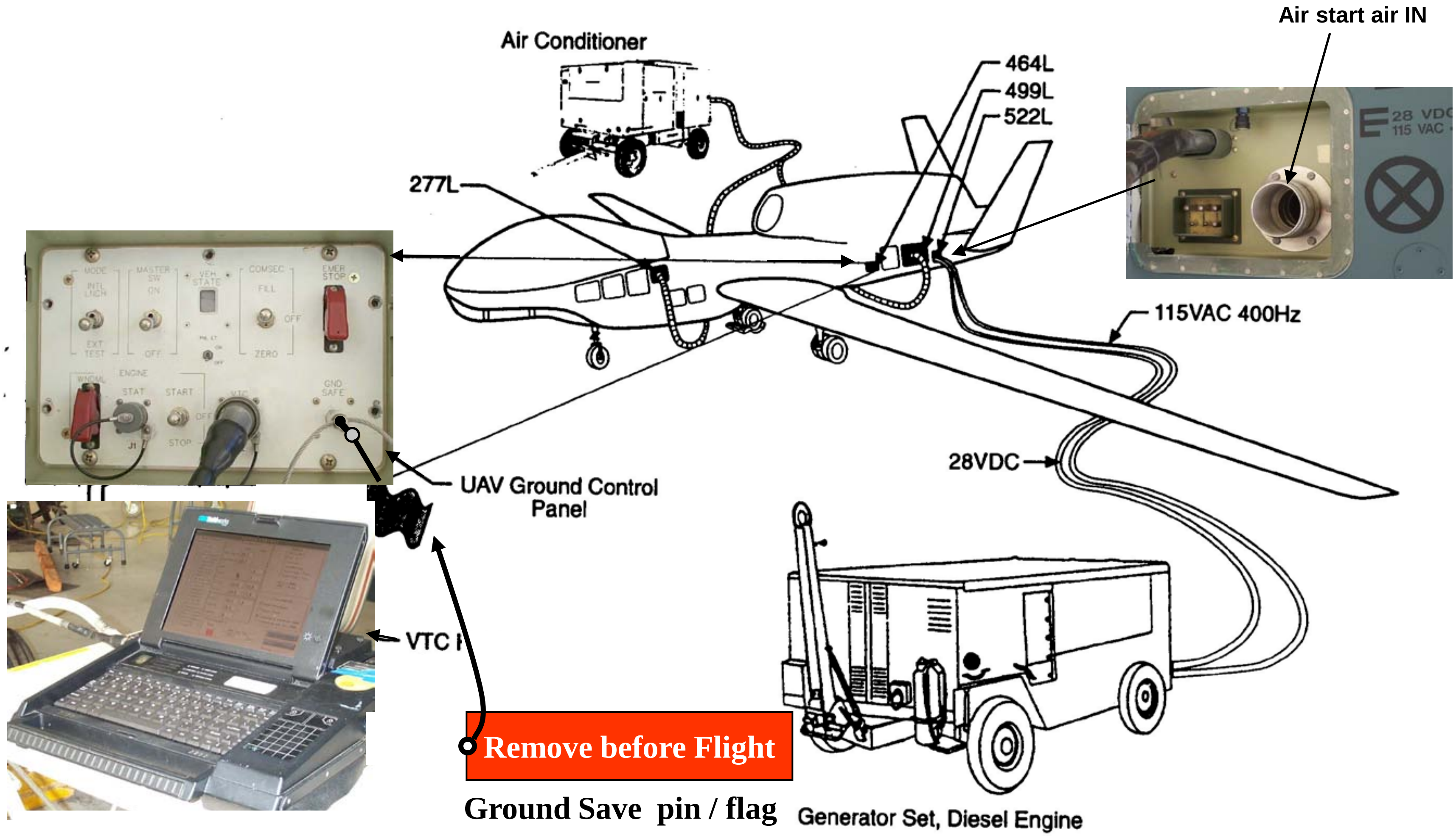
The Systems Center provides:

- An environment which exactly represents the vehicle baseline(s) and permits version management
- Test planning and procedural development for the air vehicle segment, the ground segment and any number of individual payload subsystems
- Hardware and software integration at the subsystem, segment and systems levels
- System software development, test and integration
- Mission planning and validation
- Flight control and monitoring
- Payload control and monitoring

Typical Mission Example

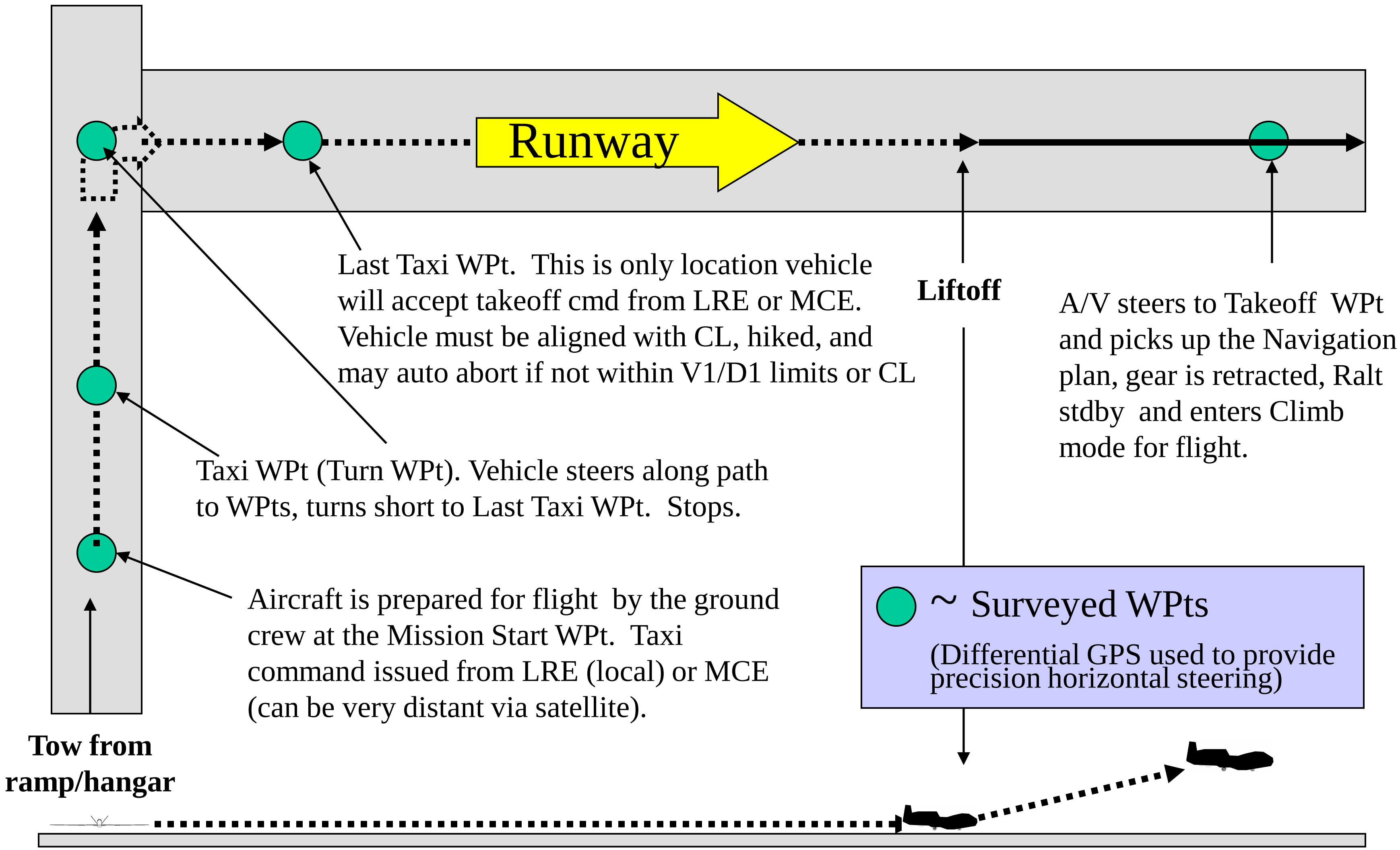
- **Mission Planning Inputs** (loaded in IMMCs at preflight)
  - Waypoint Nav Data for complete Mission Plan
  - Sensor commands for collection data
  - All Contingency actions and routes
  - All limits for guidance modes and flight control logic
- **CCO (pilot) Inputs** in flight (from LRE or MCE) as allowed by guidance modes and control laws and logic. Pilots can;
  - Control vehicle heading (off mission plan) for ATC or sensor needs
  - Set altitude levels, climb/descent rates for ATC or mission needs (within limits)
  - Control onboard radios, IFF, re-task sensor collection type / locations
  - Revise temporary routing for ATC or mission needs
- **Guidance Modes and Mode Transition Logic** enforced throughout flight
- **Flight Control Laws and Logic** enforced throughout flight

Pre-flight Checkout

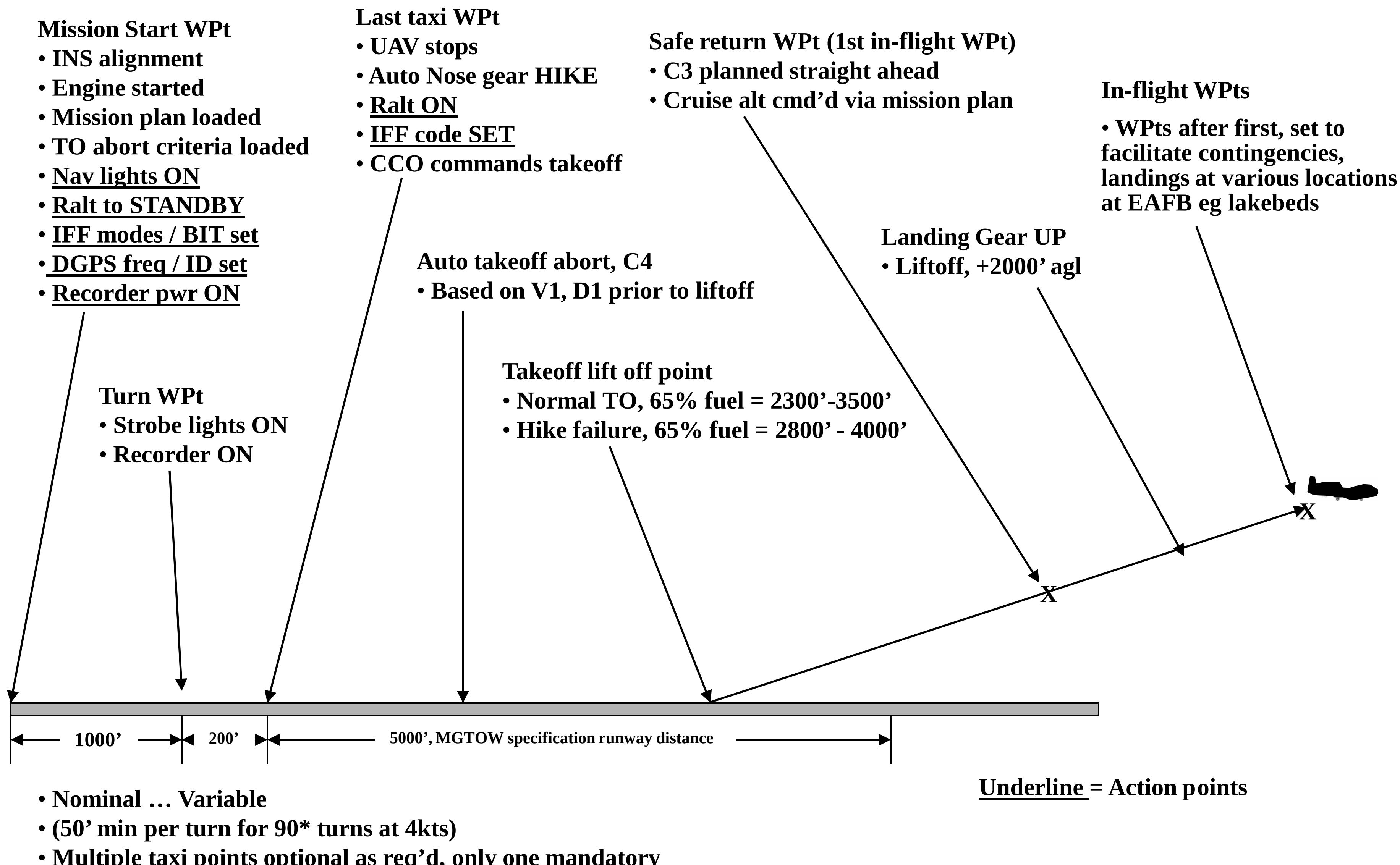


Ground Save pin / flag

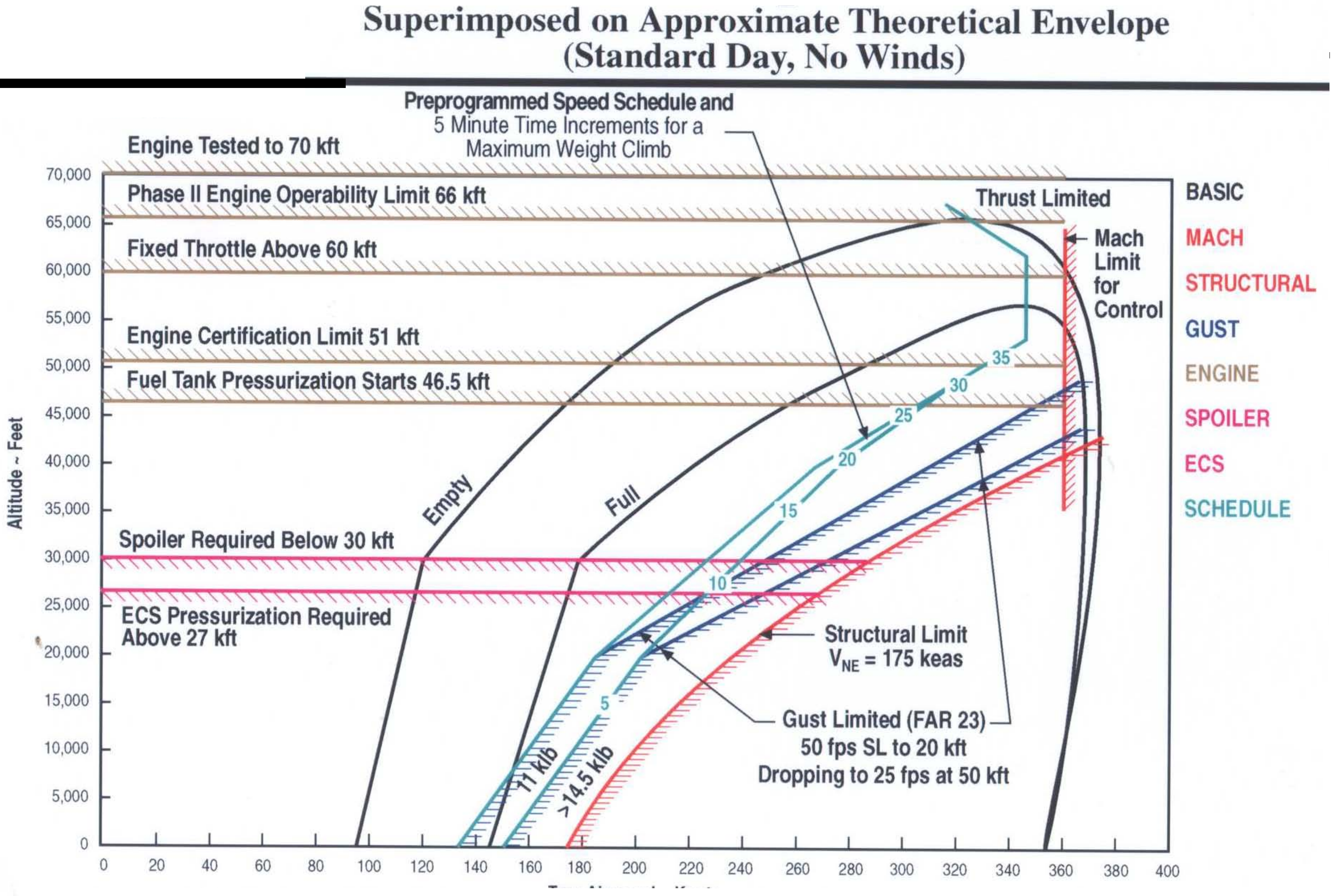
Mission Start Waypoints



Normal Taxi / Takeoff / Departure

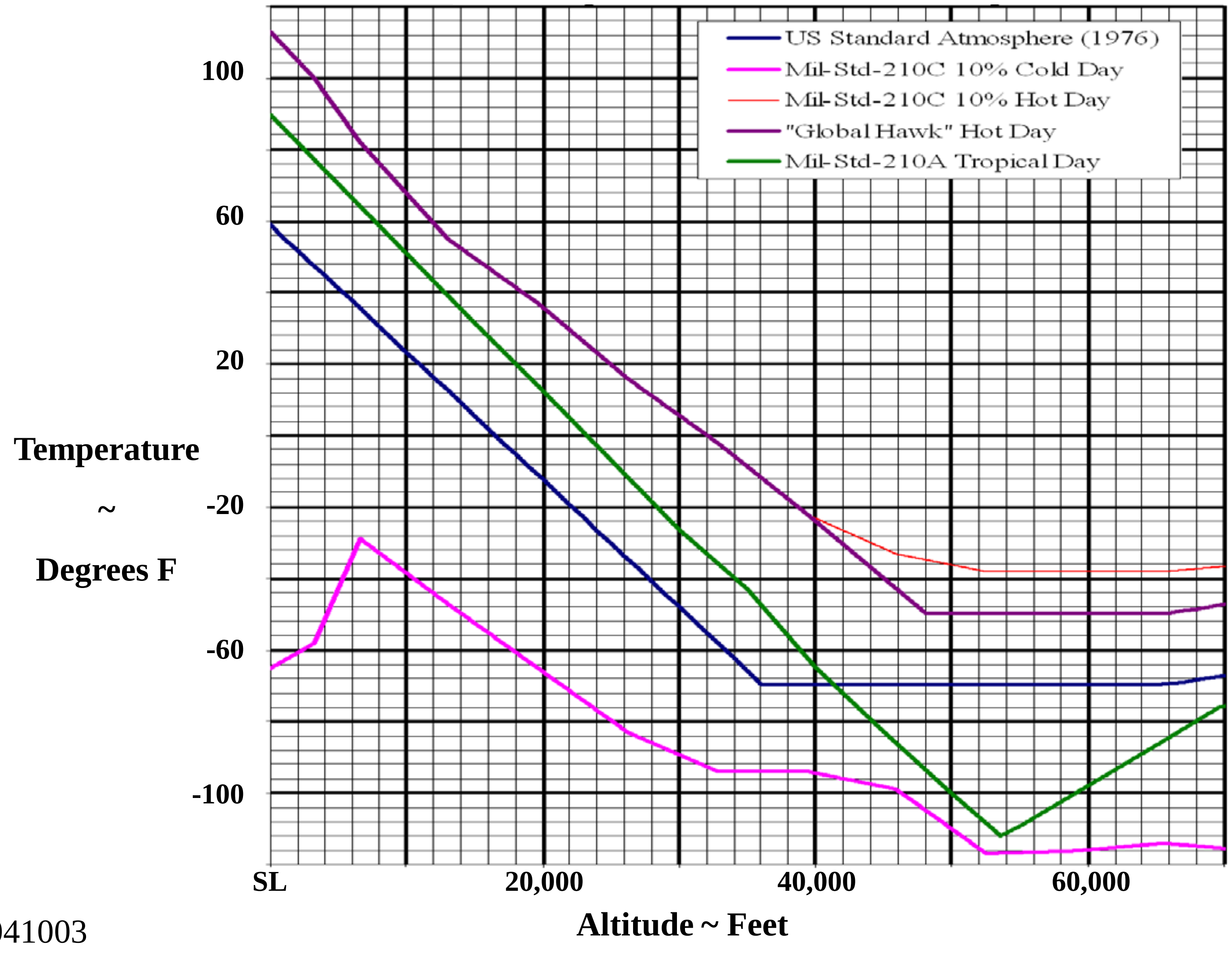


Speed Schedule

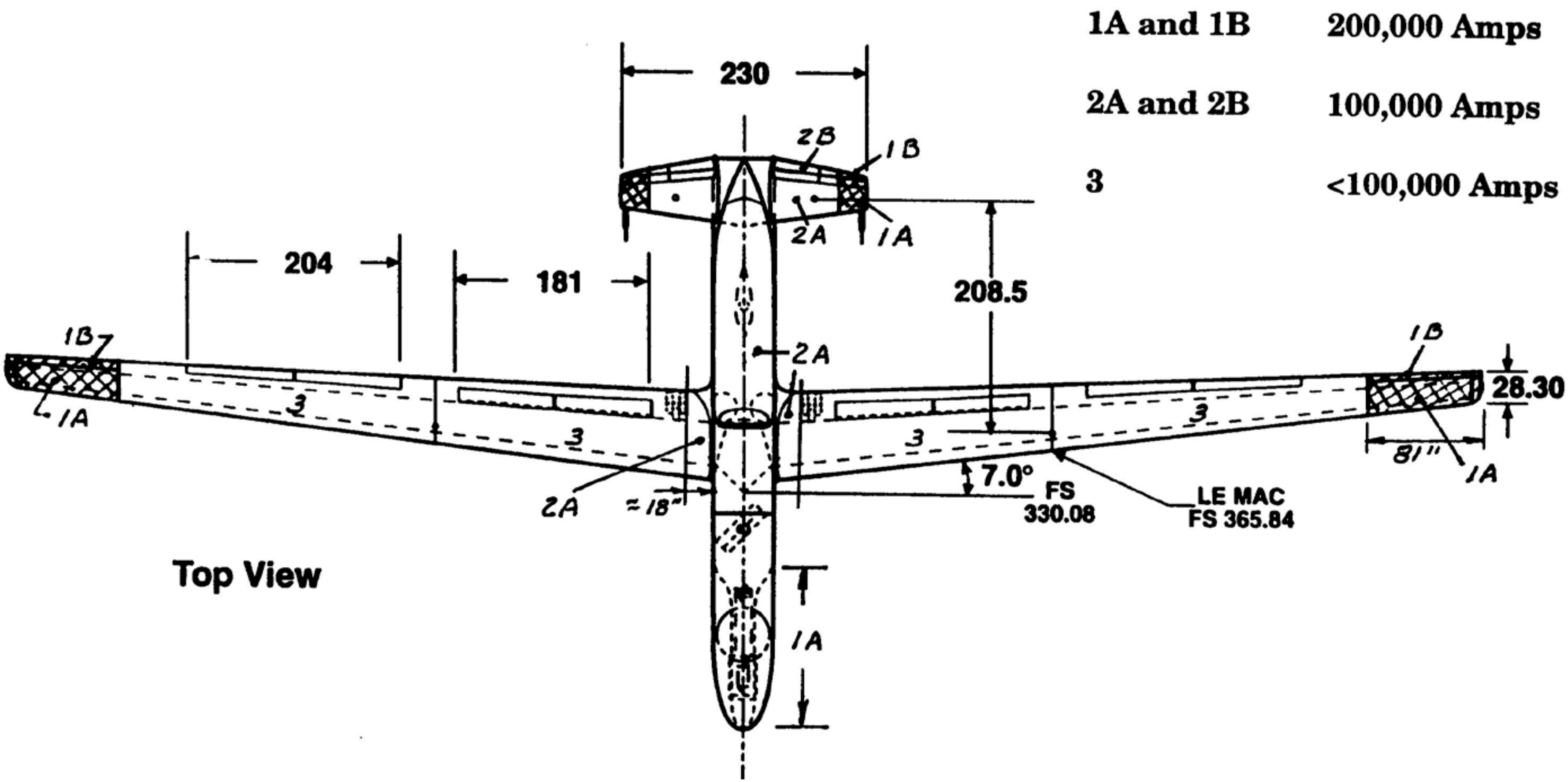


Atmospheres

Aircraft Temperature Envelope

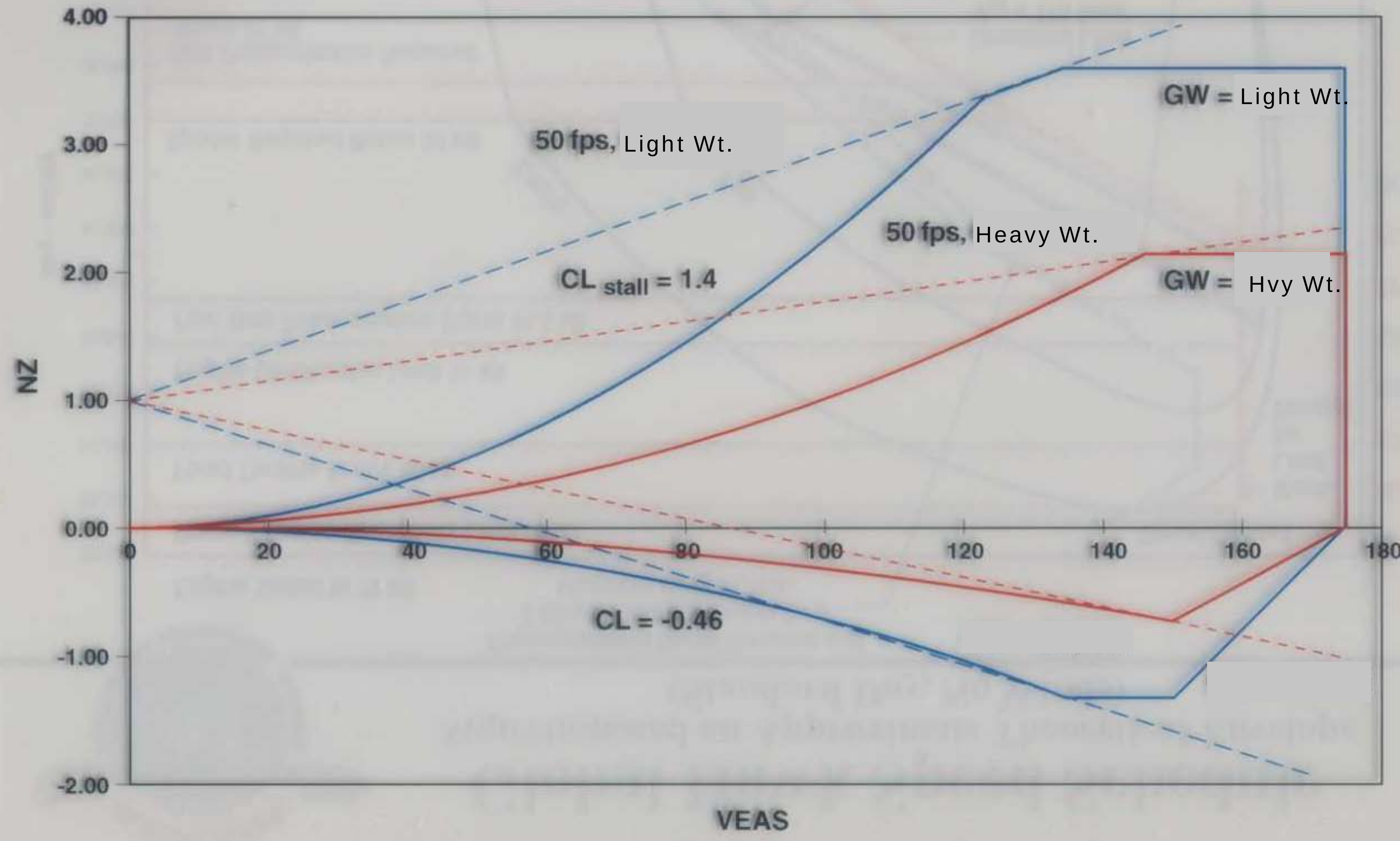


Lightning Protection Zones

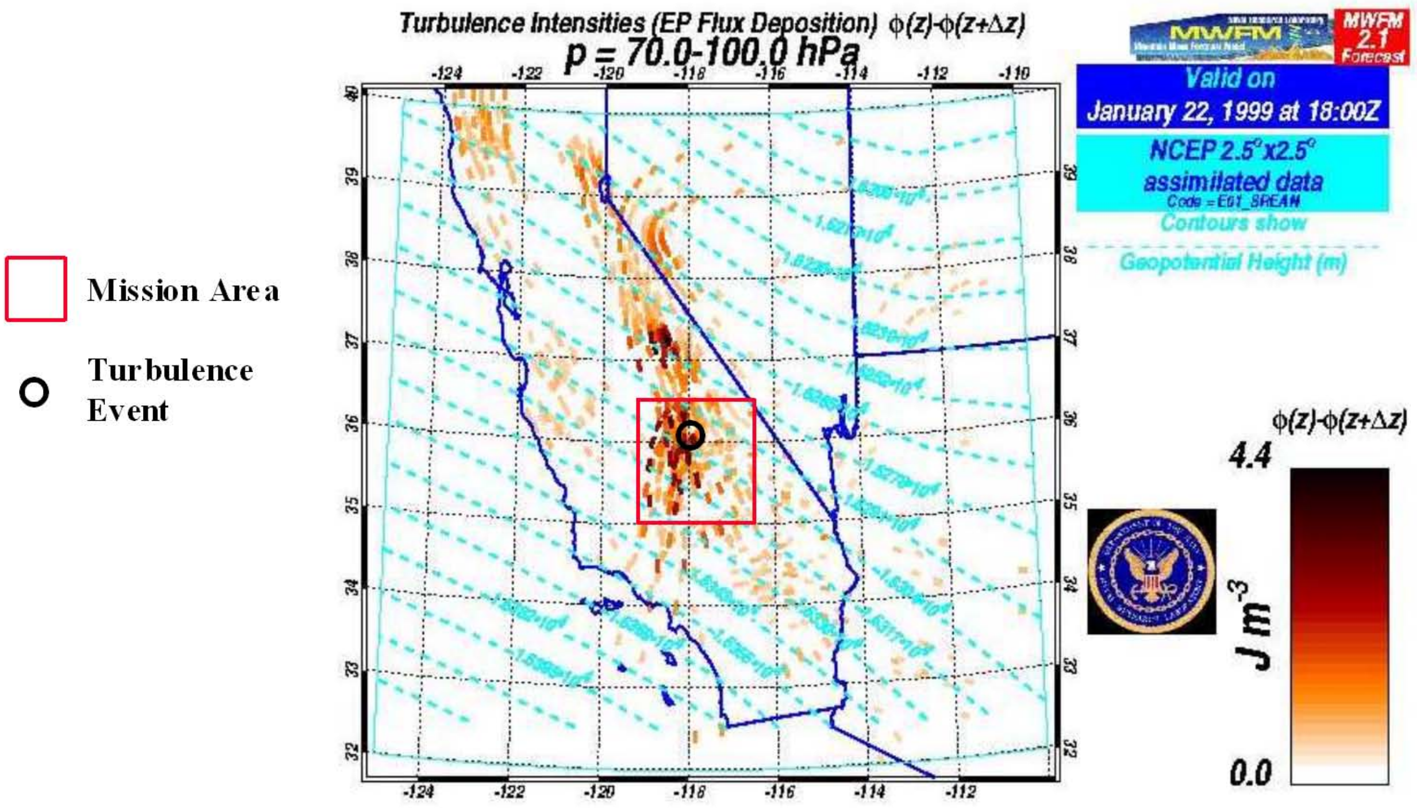


Aircraft Must Still Protect Itself and All Internal Equipment

VN Diagram
Sea Level



January 22, 1999 Turbulence Intensity FL531 to FL605 , 18:00Z



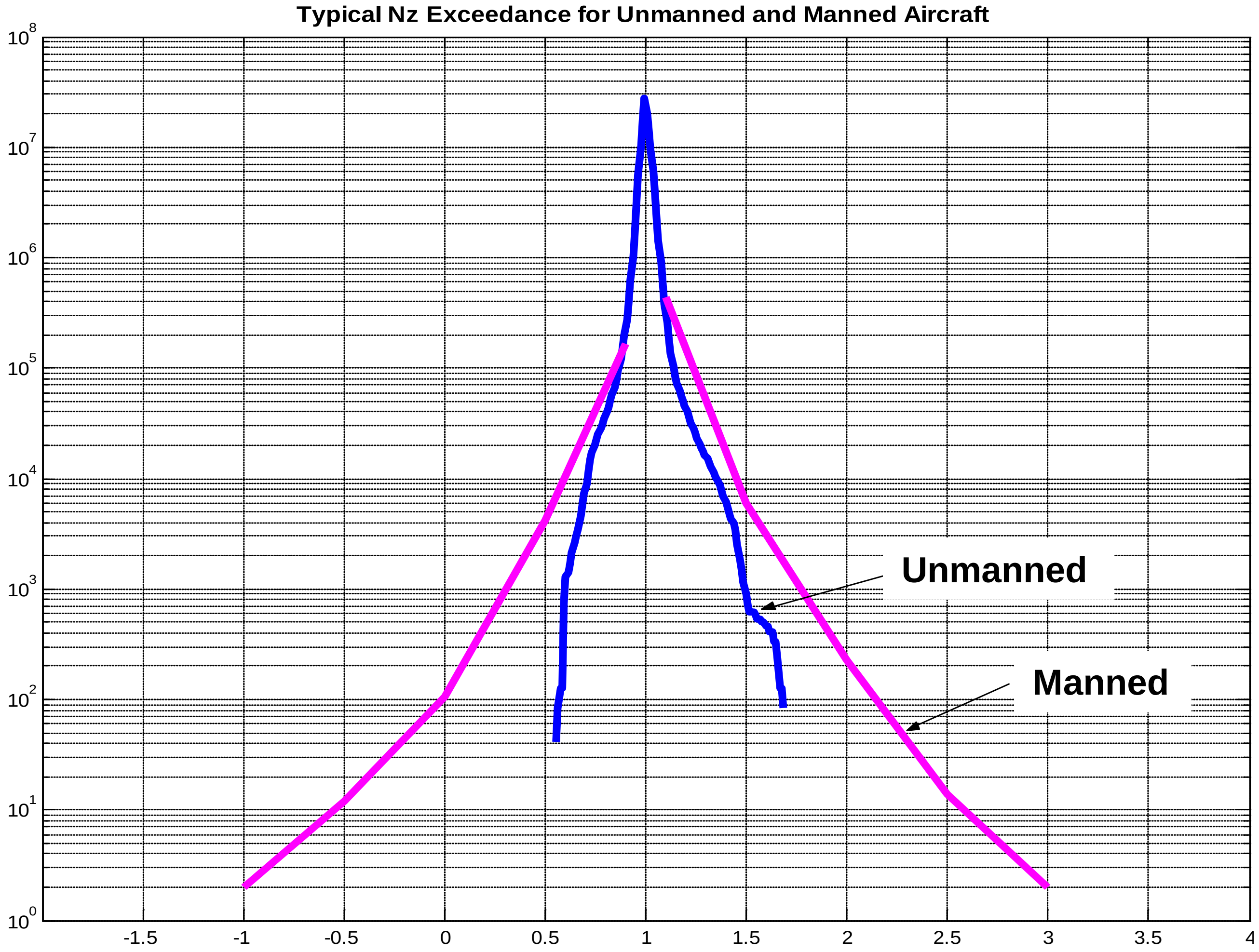
Exceedences Experienced

On-Station Operating Stress Is Benign
Nz Exceedance for Worst-Case Turbulence Flight

Gust

Exceedance

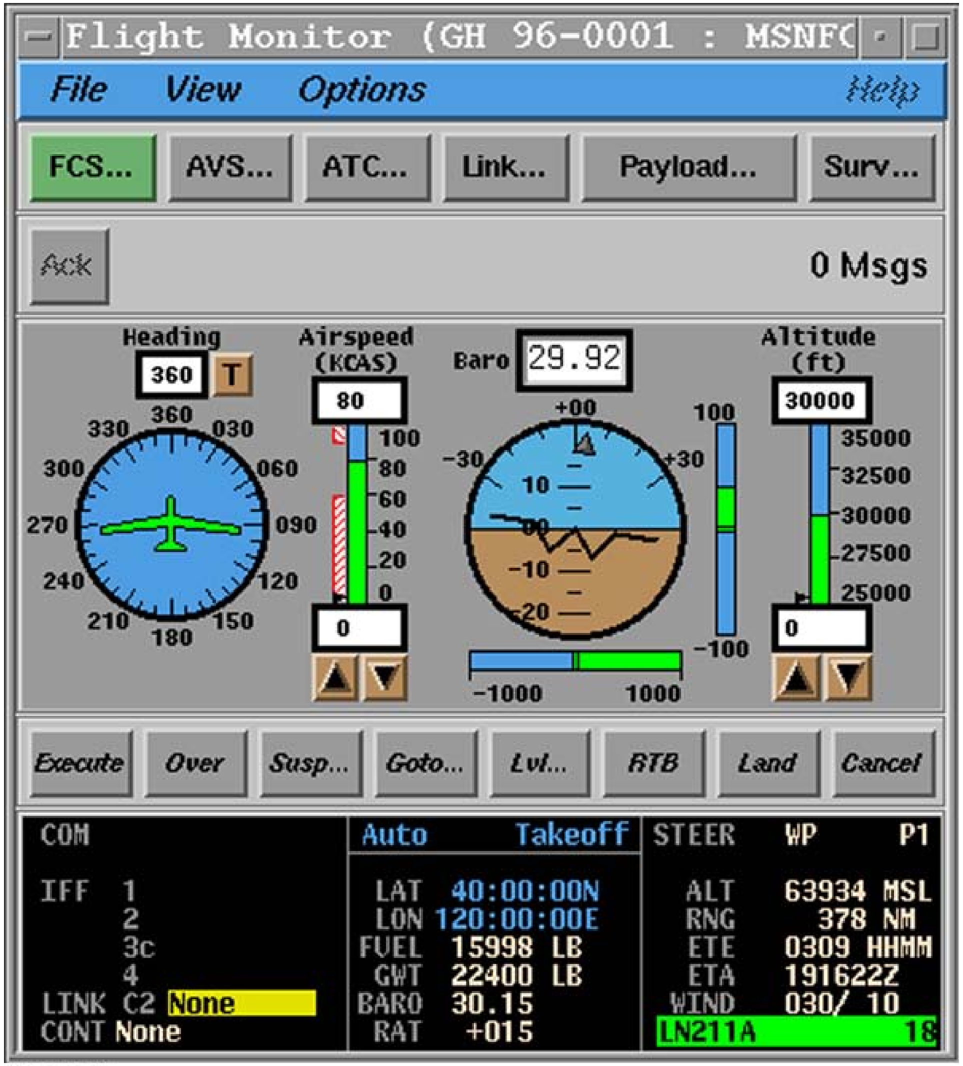
(1000 Hrs)



Nz ~ g's

Mission Monitoring, an MCE

An Example of a Flight Control HCI



H367-0243

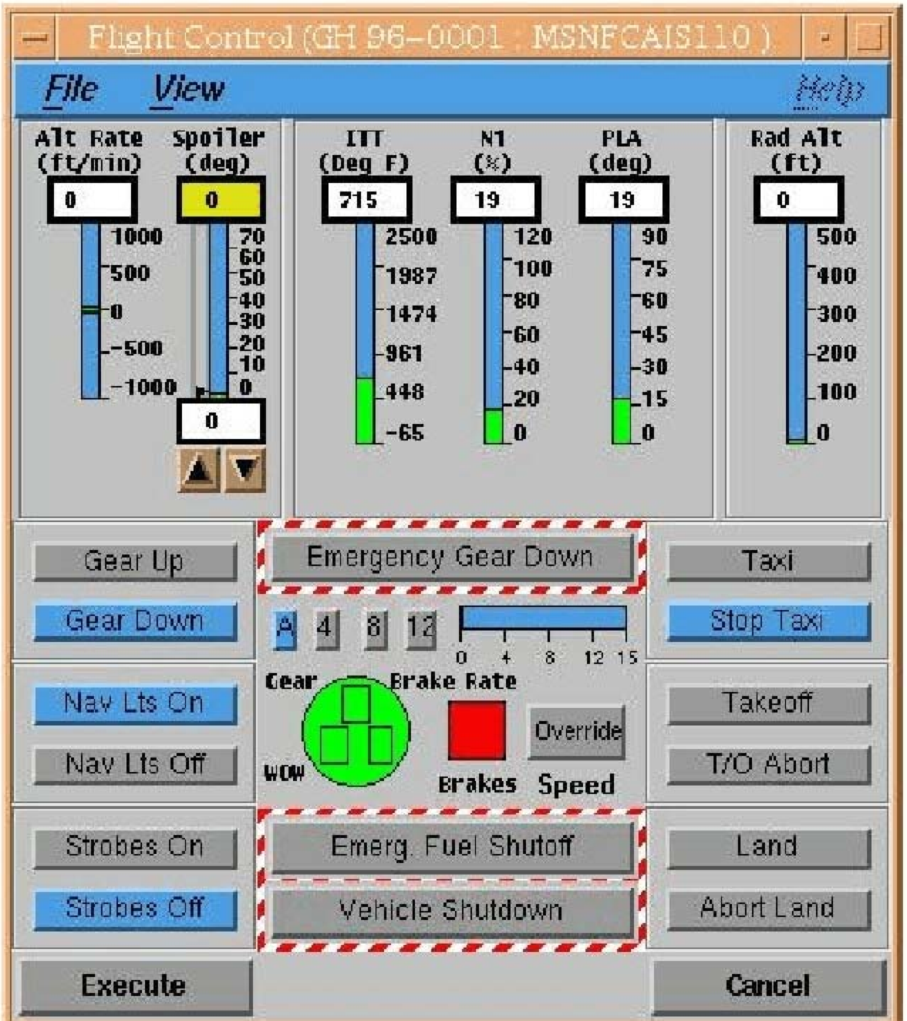
Flight Monitor HCI

This **H**uman **C**omputer **I**nterface screen is readily recognized by most pilots and is used to interpret vehicle flight mode and condition, and provides the ability to control (send commands to) the vehicle by the remote operator.

Hyper-linked "Buttons" allow access to other HCI's for additional commands or access to vehicle systems status. Mouse clicks bring up these screens for continuous or periodic monitoring as desired.

Bottom section shows current autonomous systems status.

Another Screen, the Flight Monitor HCI



H367-0244C

Flight Control HCI

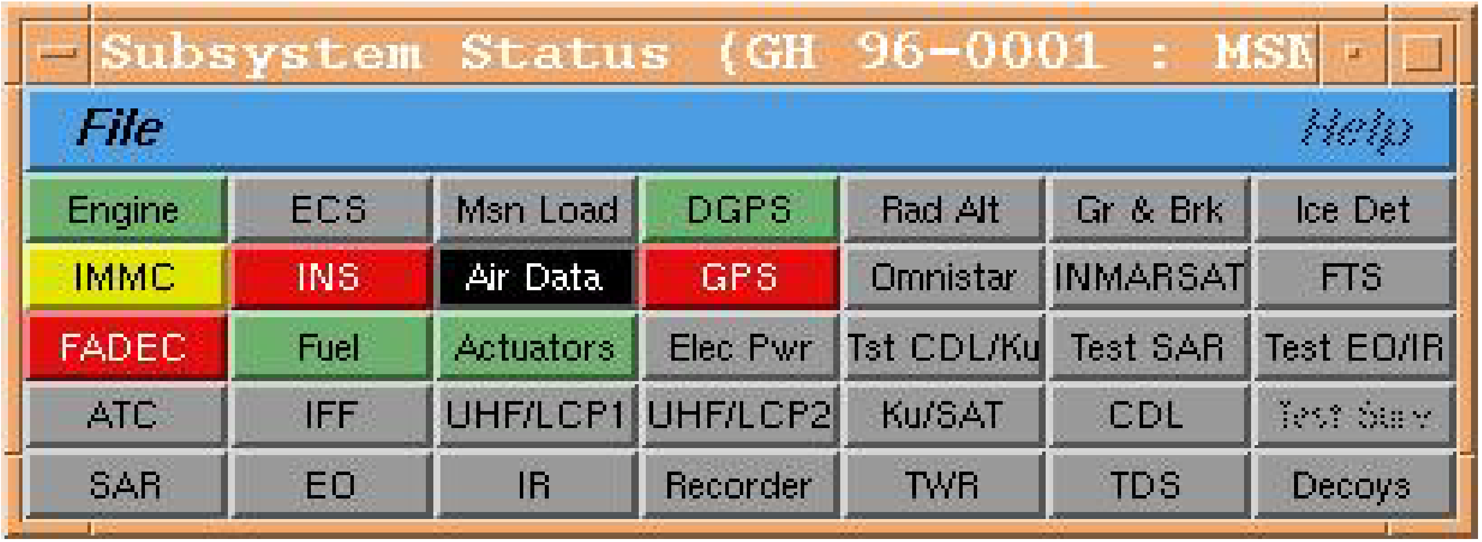
This **H**uman **C**omputer **I**nterface screen is also readily recognized, using typical “tape” displays for vehicle data.

It is also used to command basic vehicle functions via hyper-linked buttons for vehicle control.

This screen, the Flight Control and Vehicle Status (next page) HCI’s are the primary Global Hawk screens used by the pilots for air vehicle monitoring and control.

Additional HCI’s are used for Nav, sensor operation and communications functions.

The Air Vehicle Status HCI

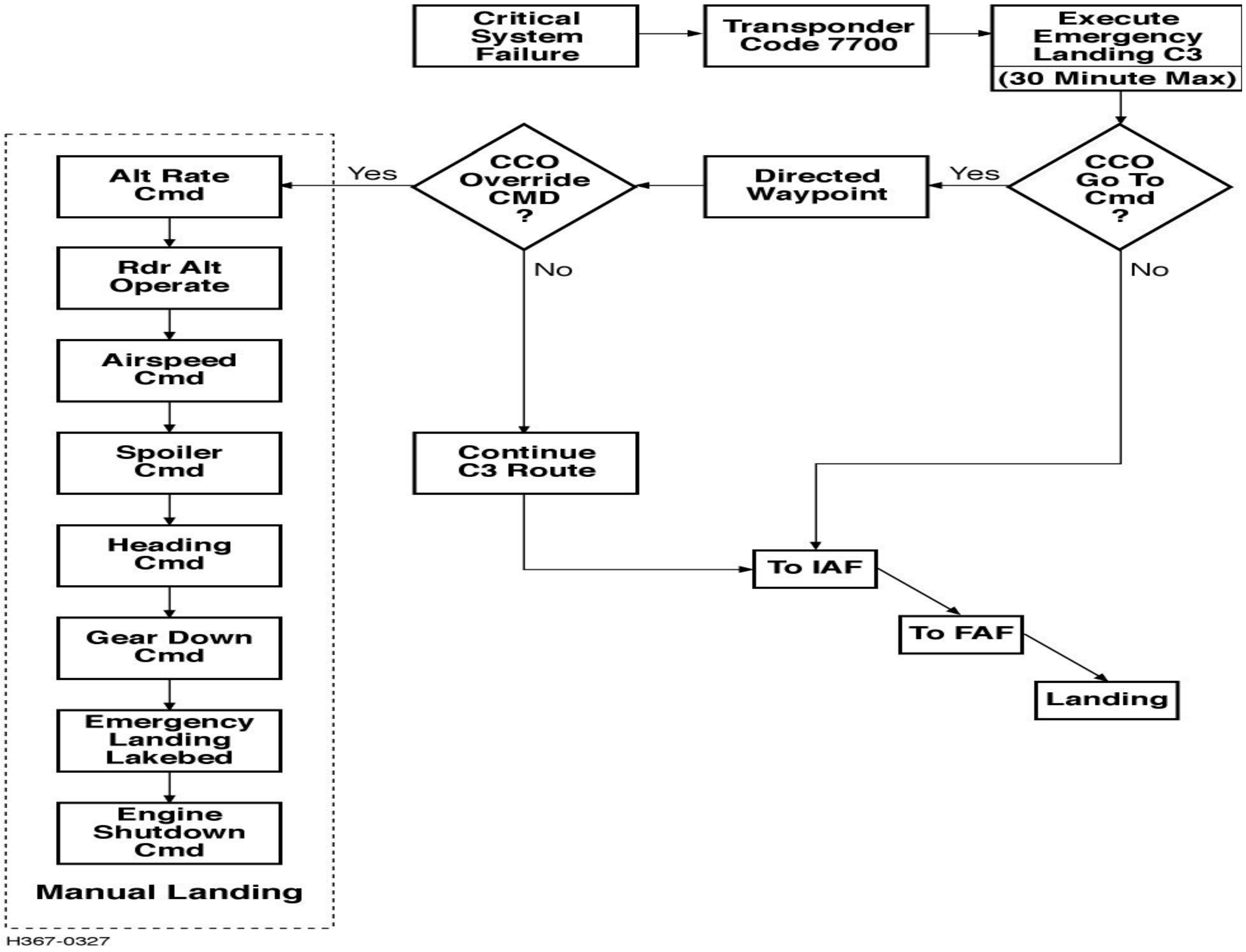


H367-0245A

This HCI, the Air Vehicle Status screen (available from the Flight Control HCI, via the **AVS** button) is the pilots way of maintaining his continuous view of the vehicle health. Data is continuous down-linked to the ground stations with the status of each system. These Green, Yellow, Red, and Flashing **Red** buttons reflect the status of each system. Additional HCI's are available under each of these buttons for complete pictures of that specific systems status at any time for evaluation by the pilot.

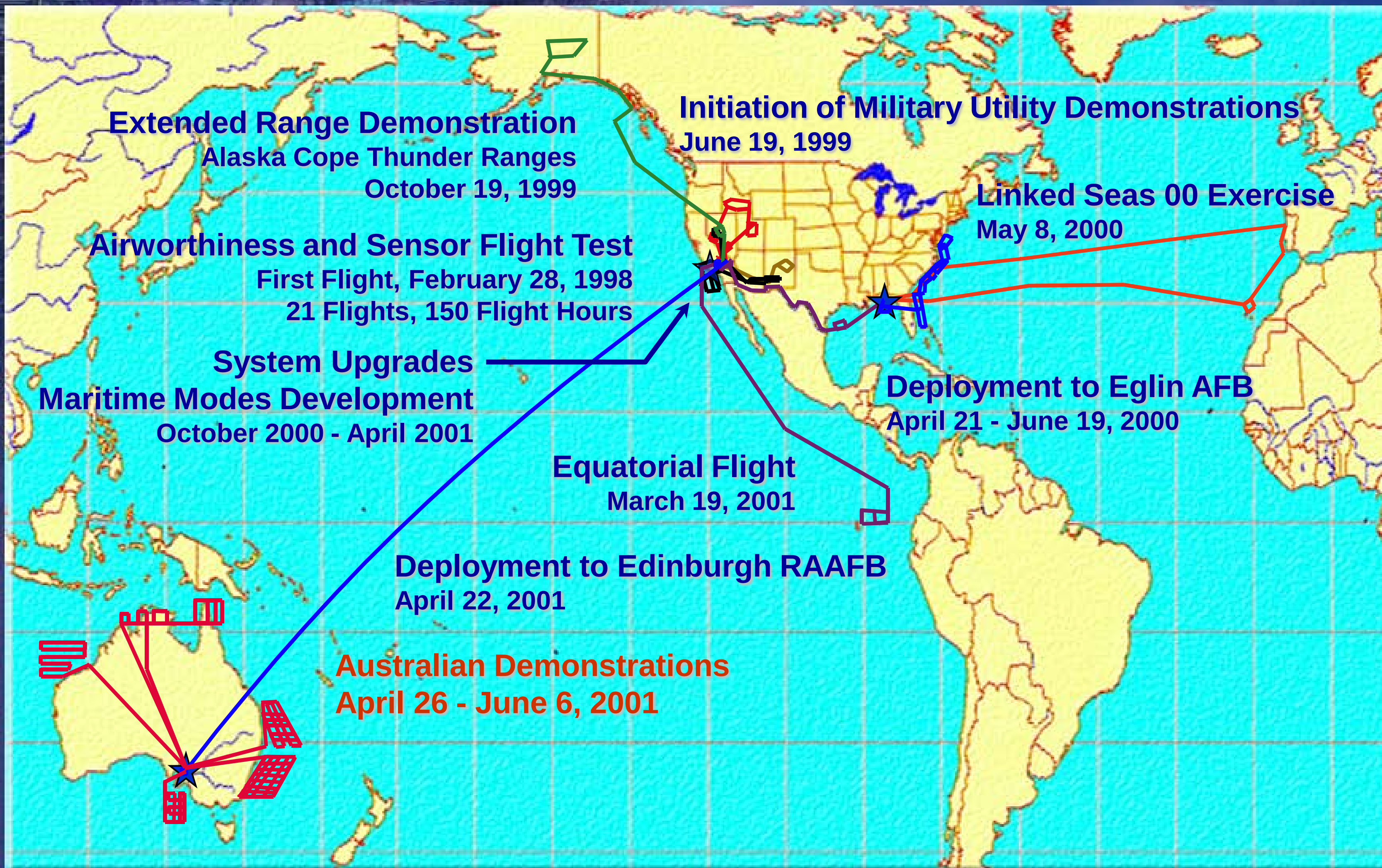
For example, the ECS status can be monitored when flight temperatures are extreme to predict vehicles' potential for going Yellow, Red or Flashing Red and take preemptive actions as appropriate to continue the mission.

Typical Emergency Logic Tree, Flashing Red

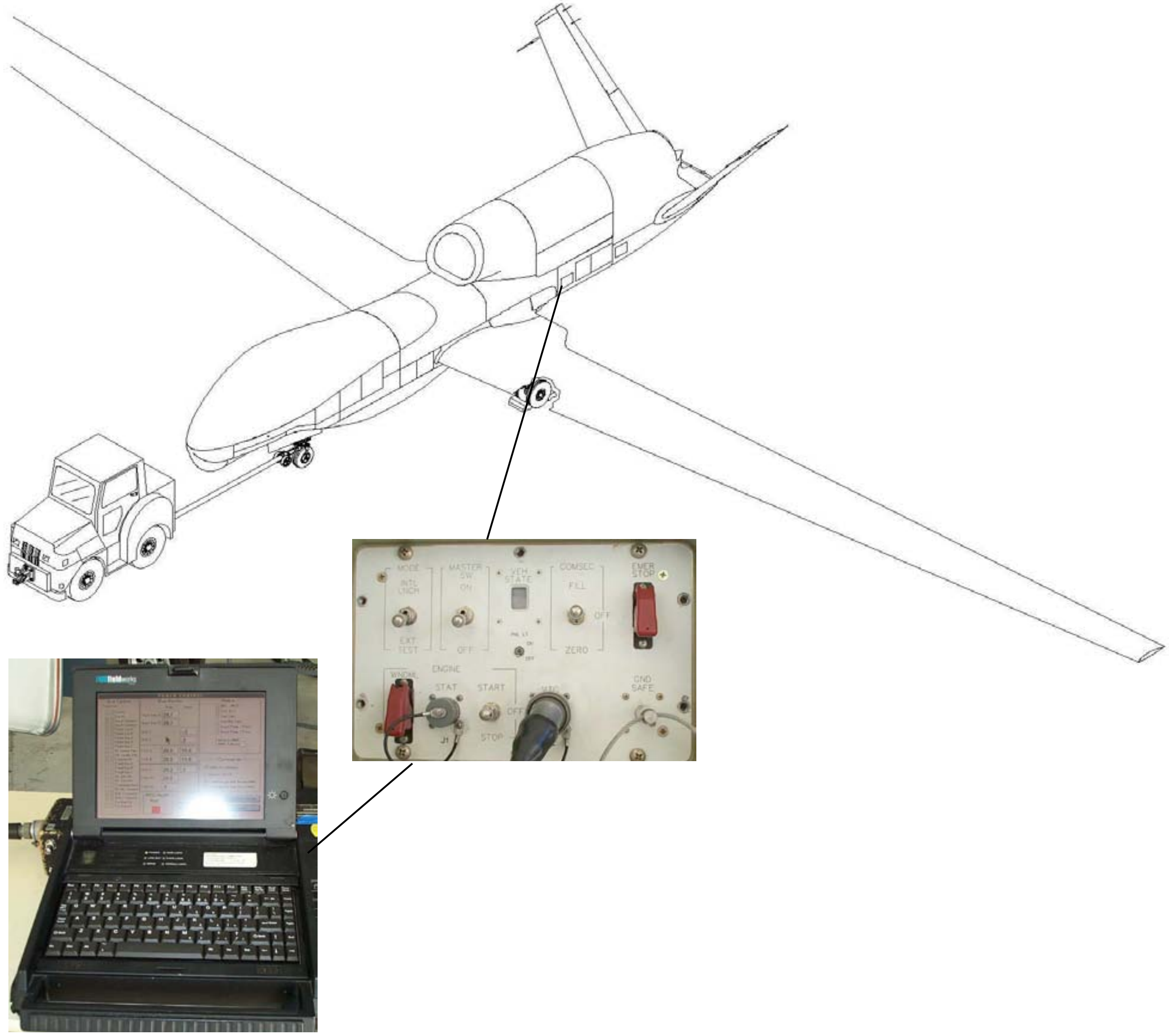


Examples of Autonomous Operations

Flight Operations Summary



Post-flight Checks




U.S. AIR FORCE

Summary

1. **UAVs will demonstrate lower operating costs and will satisfy or exceed user requirements**

2. **World Wide Operations (WWO) will require significant levels of reliability and redundancy**

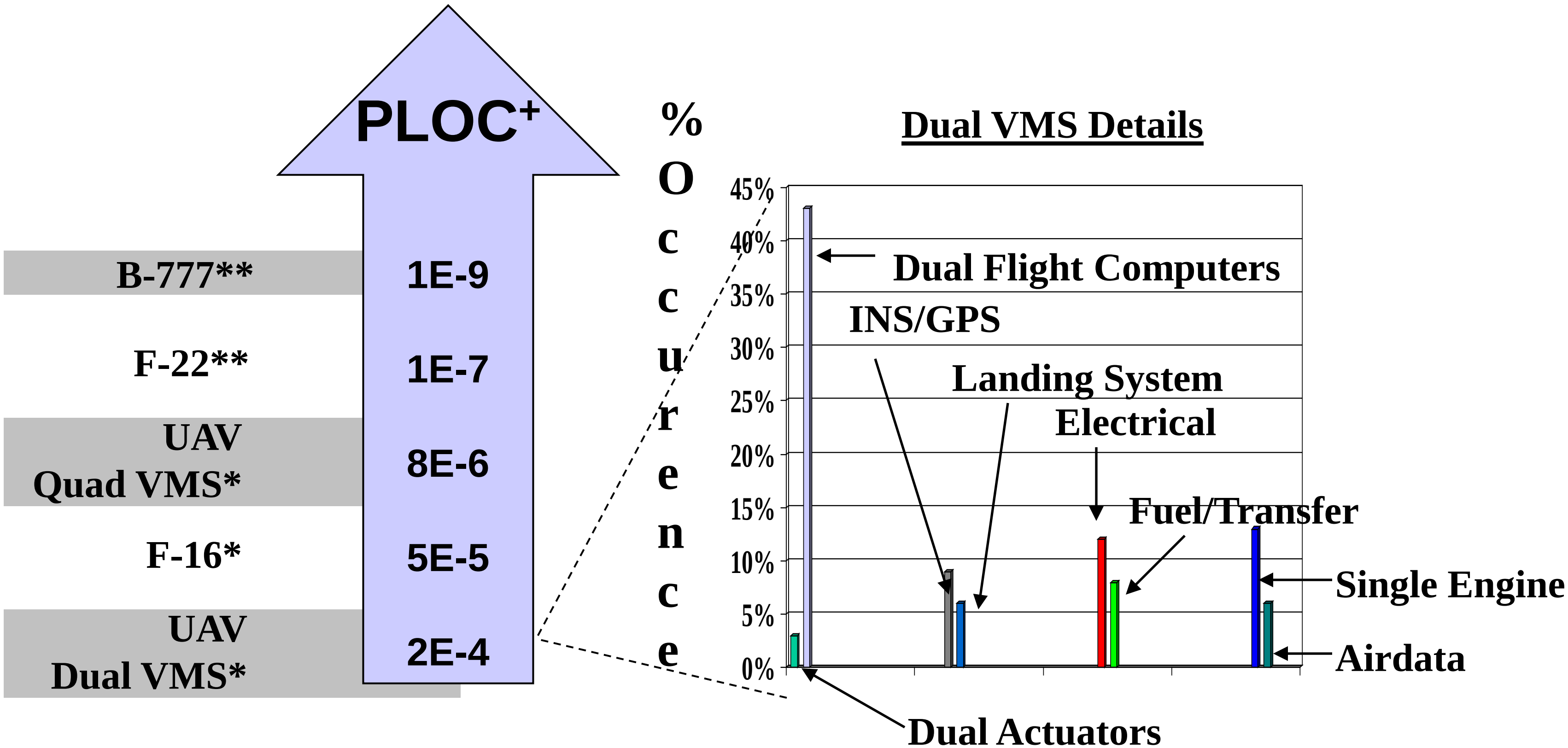
3. **Reusable UAVs are part of a network centric system**

4. **Ground segment importance will diminish with increased autonomy on the UAV**

BACKUP

Typical Dual VMS Aircraft Loss Rate Comparisons

(Based on Analysis for 100% of Engine Failures Result in UAV Loss)



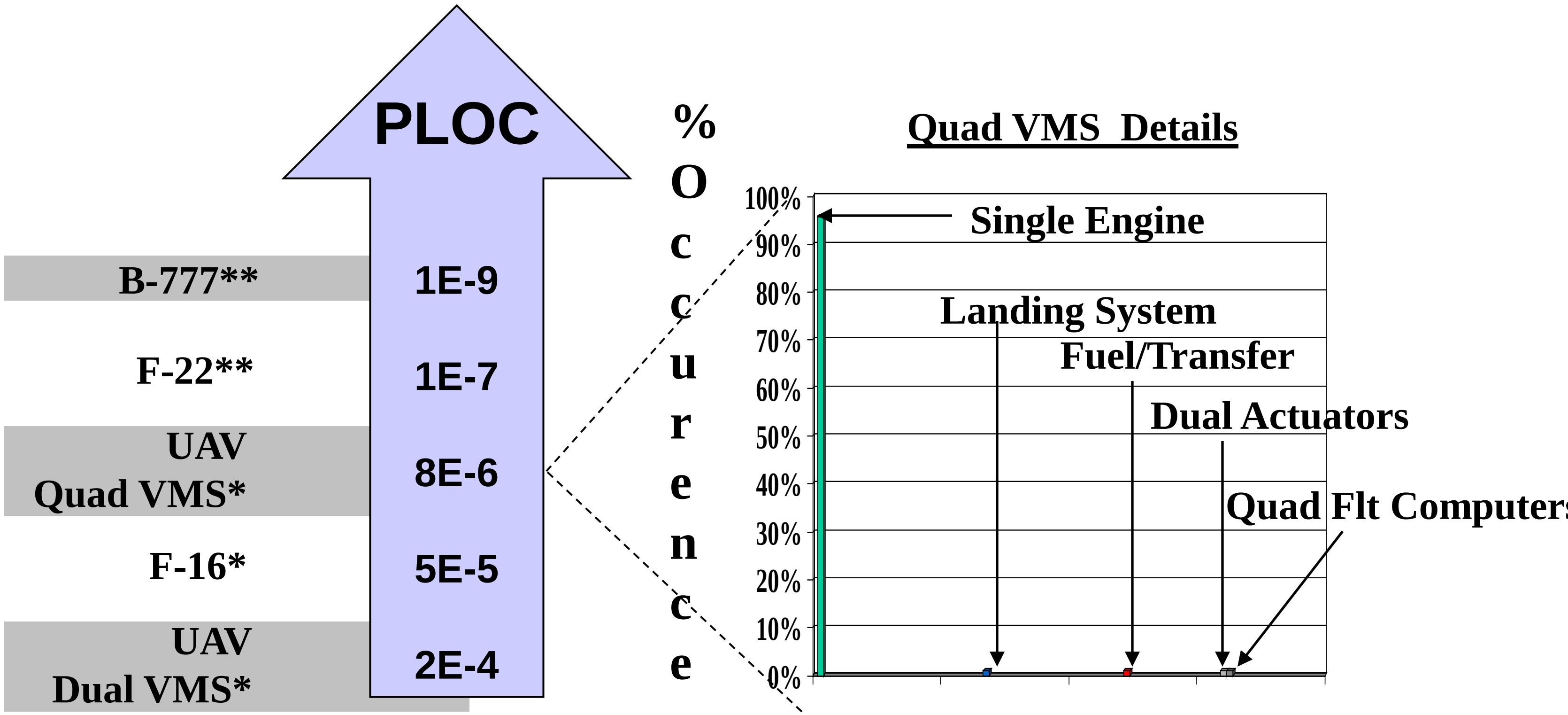
***** Includes Propulsion System Failures

** Failures Due to Redundant VMS Only

+ Probability of Loss of Control

Typical Quad VMS Aircraft Loss Rate Comparisons

(Based on Analysis for 100% of Engine Failures Result in UAV Loss)

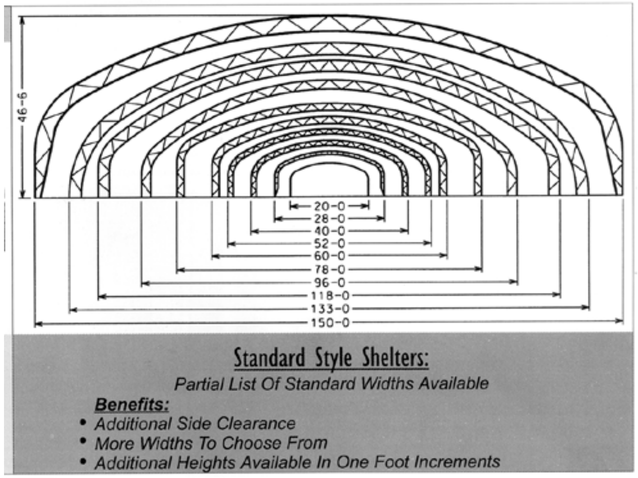


Note - Systems with Very small Contributions were Deleted

***** Includes Propulsion System Failures
** Failures Due to Redundant VMS Only

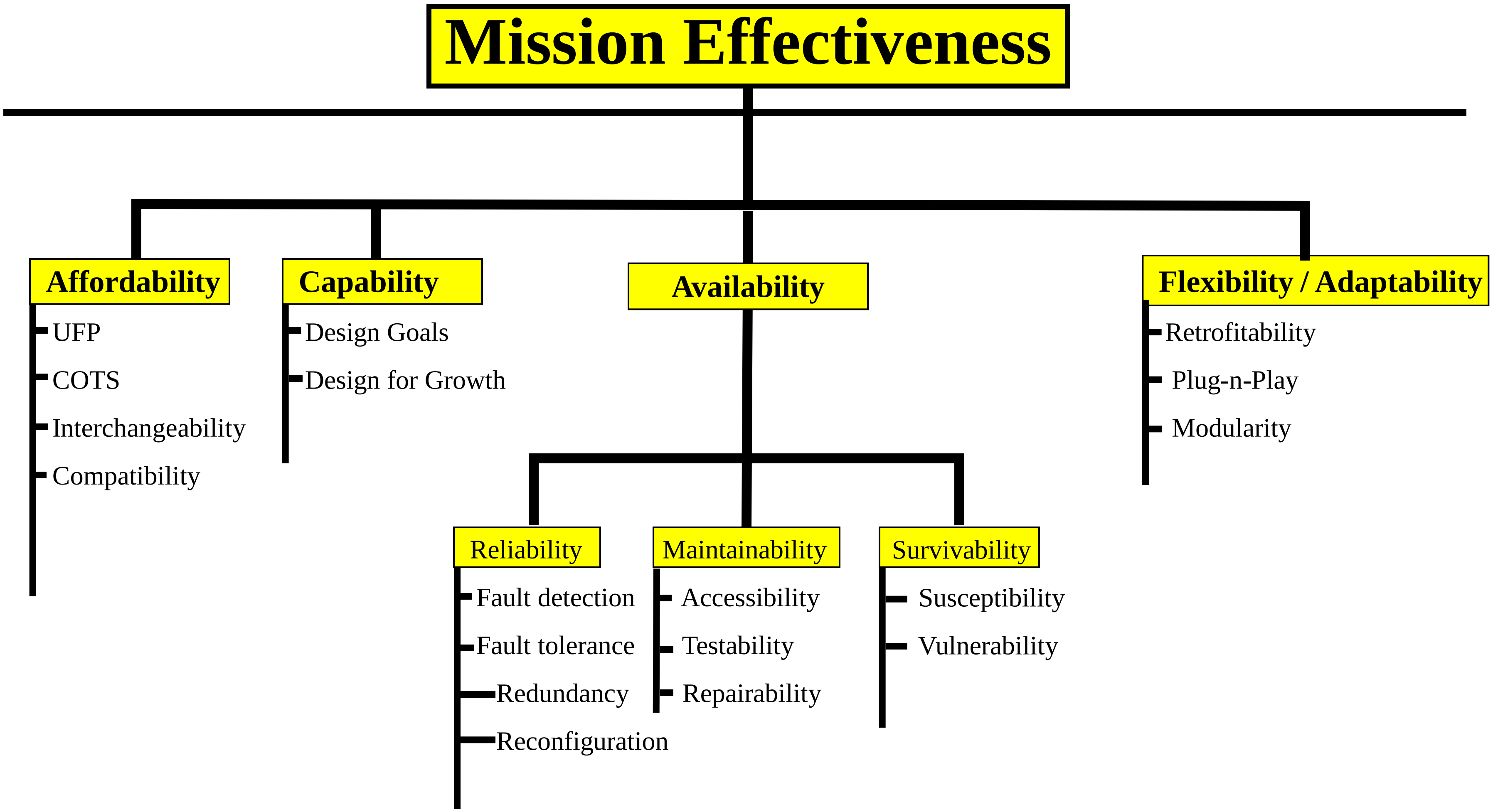
Design Requirements

Temporary Hangars



Reference: BigTop Manufacturing Co
3255 N US 19, Perry FL 32347
Item = 150' x 80 x 36 x 10
Item = 166' x 80' x 36' x 10'
Alternate supplier is Rubb Building Systems

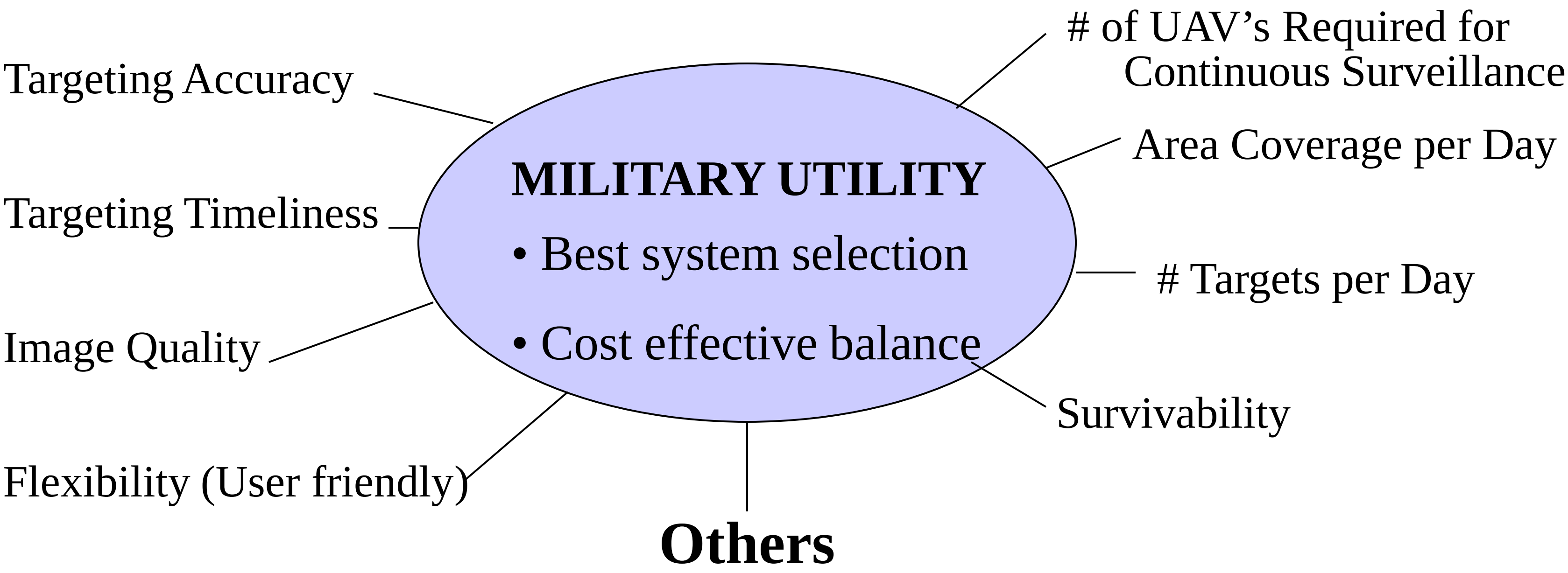
256' Hangar at Boston Logan airport by Rubb



Mission Effectiveness
Affordability
UFP
COTS
Interchangeability
Compatibility
Capability
Design Goals
Design for Growth
Availability
Reliability
Fault detection
Fault tolerance
Redundancy
Reconfiguration
Maintainability
Accessibility
Testability
Repairability
Survivability
Susceptibility
Vulnerability
Flexibility / Adaptability
Retrofitability
Plug-n-Play
Modularity

Utility Model

Utility Elements

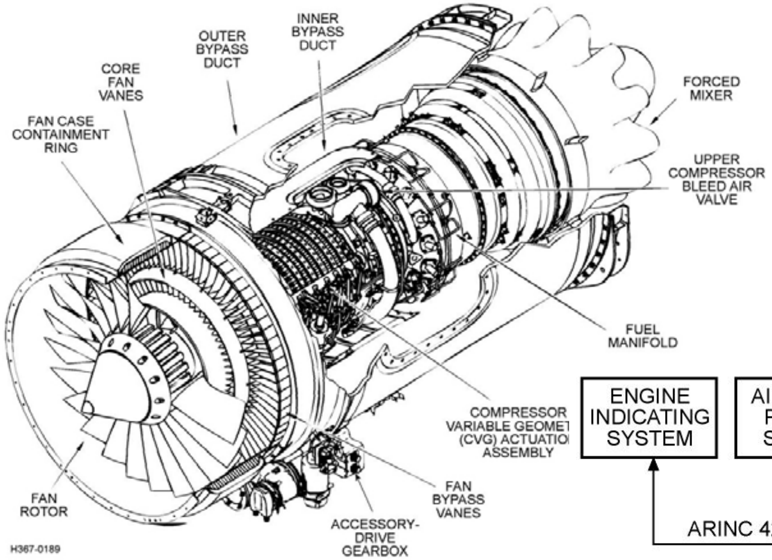


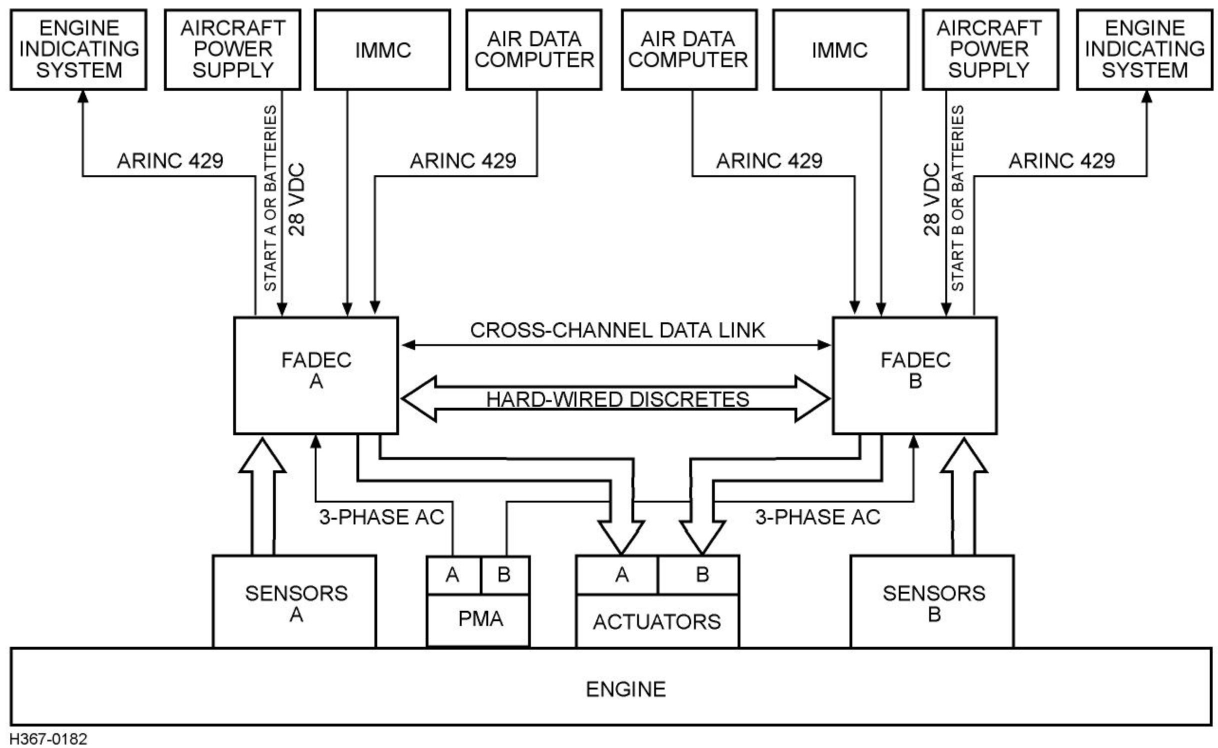
Design Implementation

&

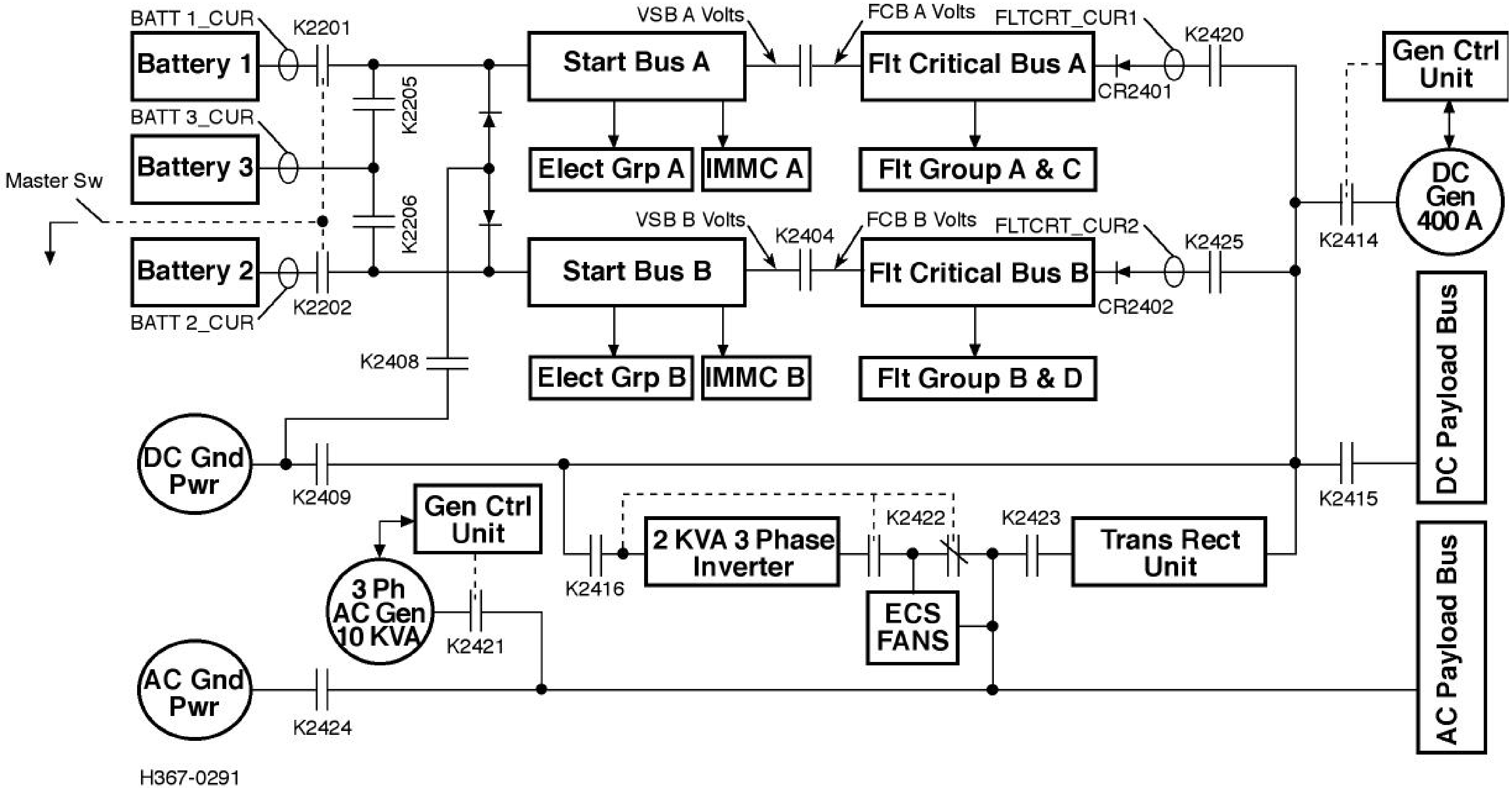
Design Specifics

Engine and Control System

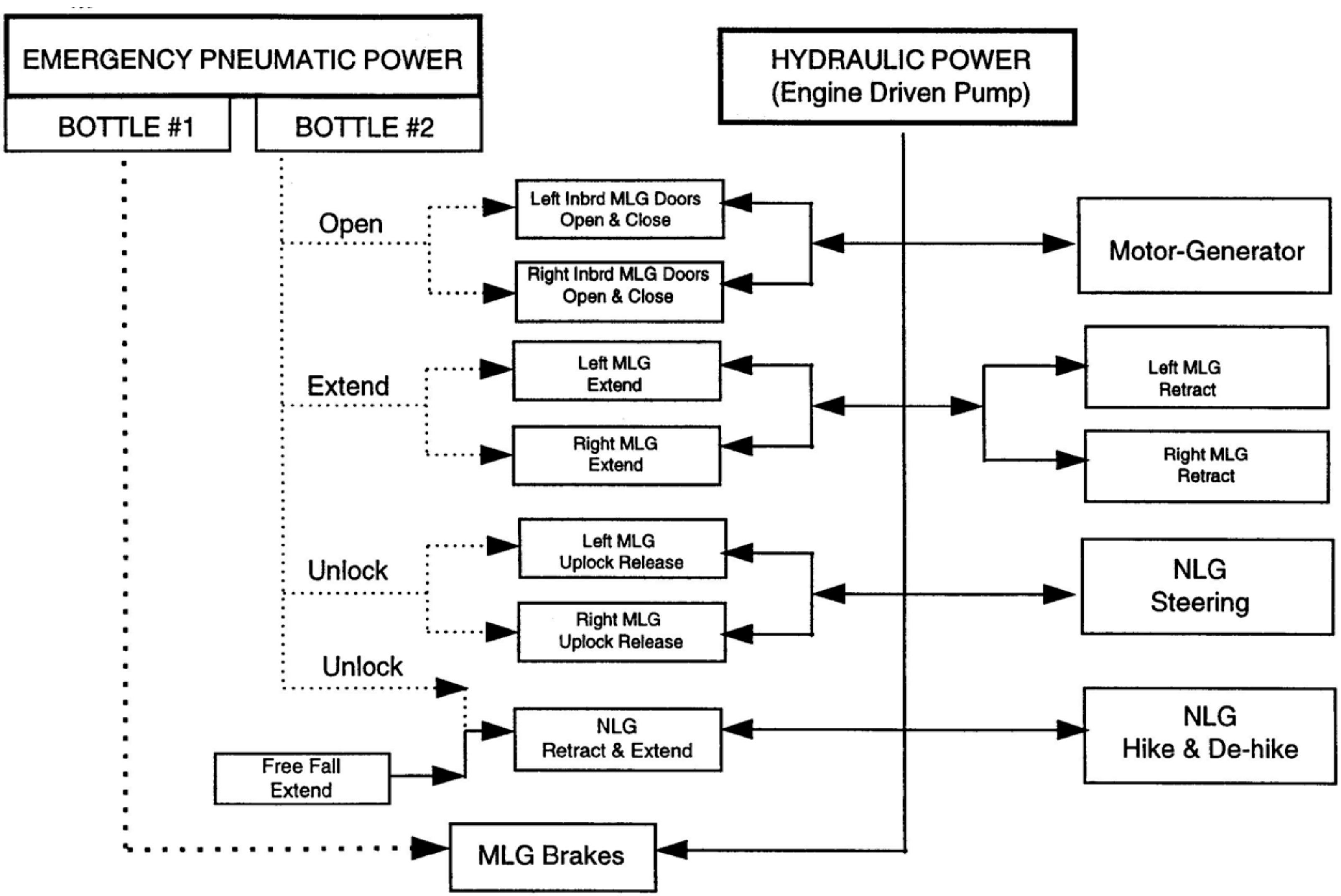




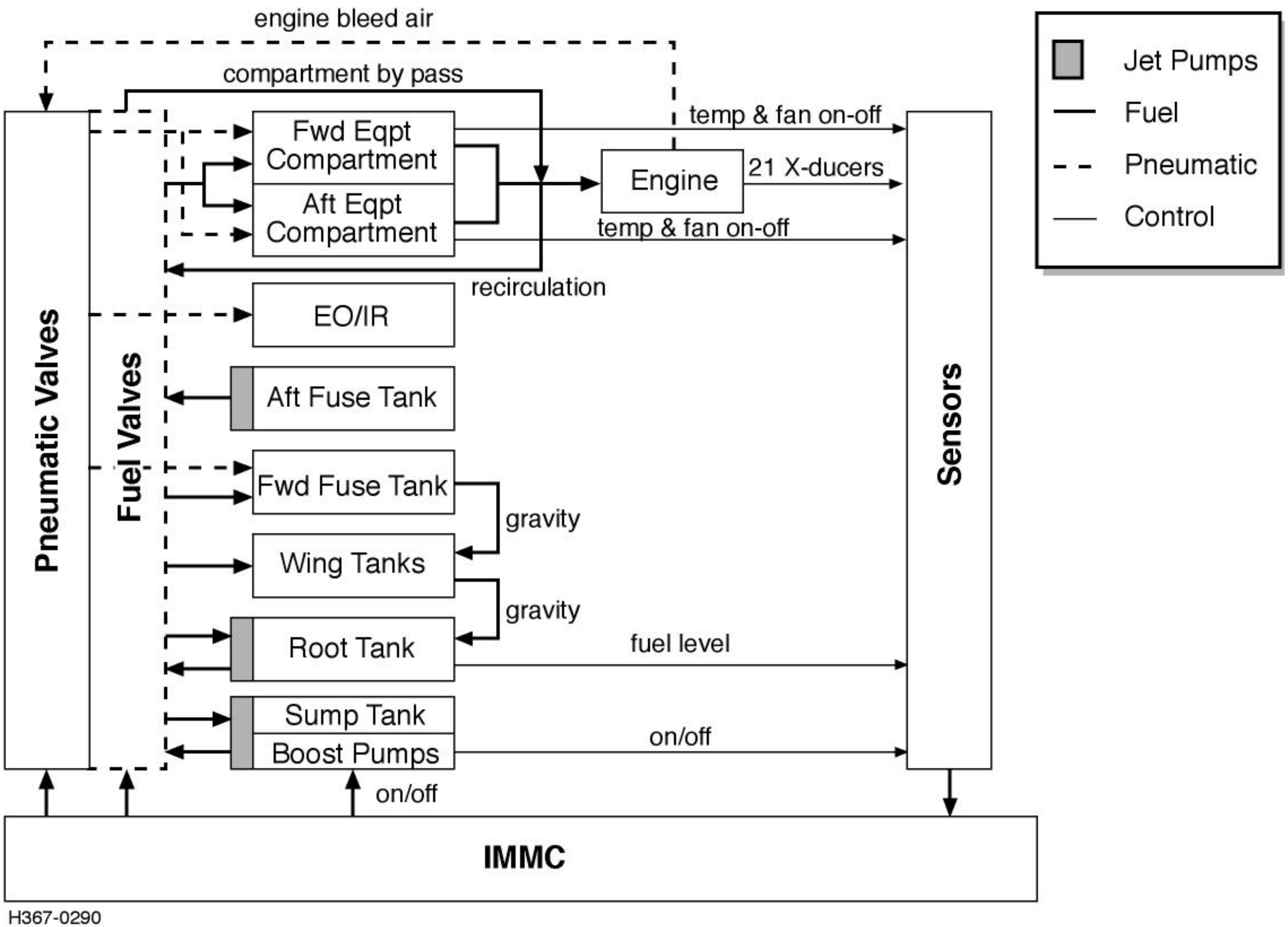
Electrical Power Schematic



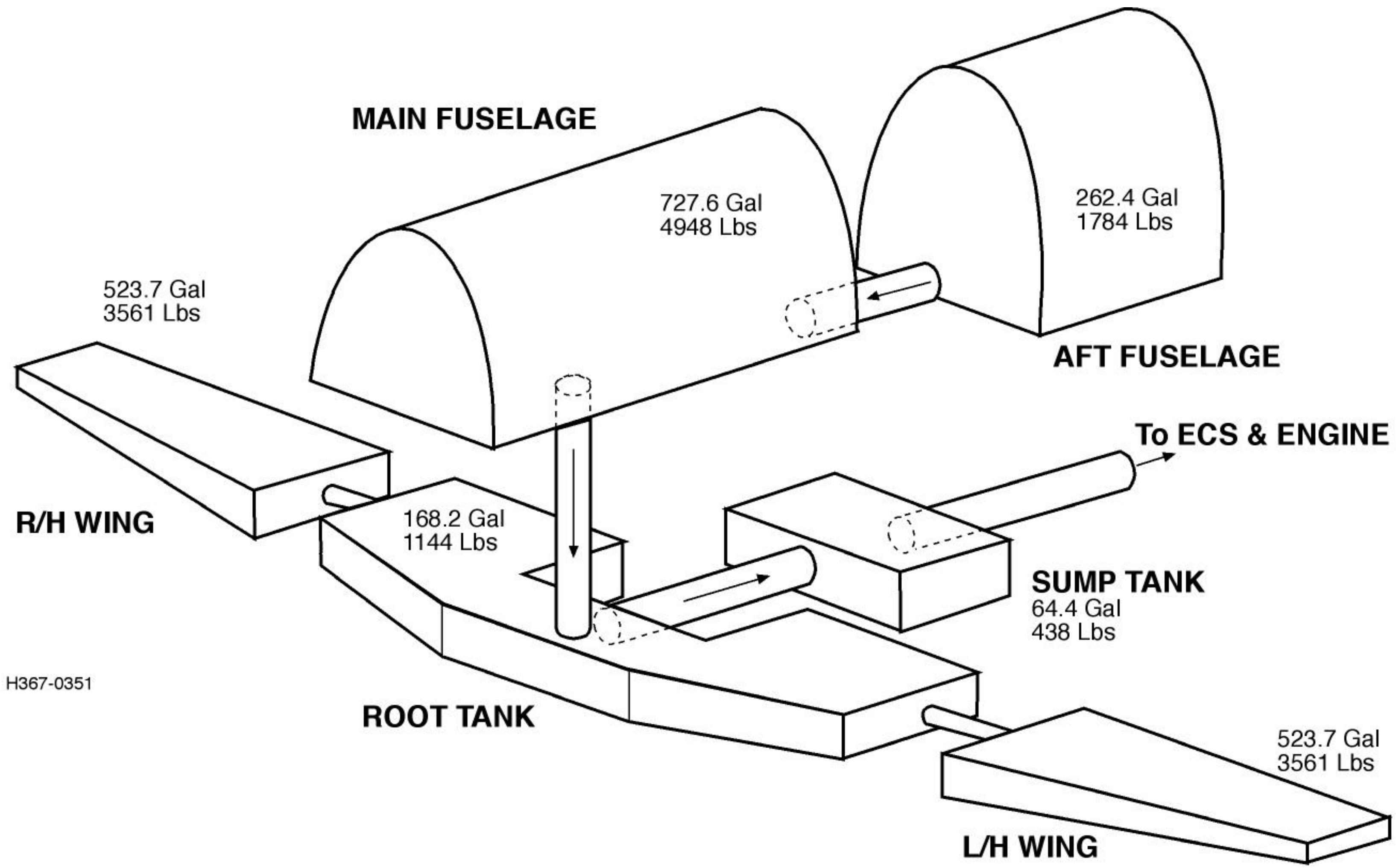
Hydraulic Block Diagram



Vehicle Fuel System Schematic



Fuel System Pictorial



Single Event Upsets >≅ 40 K Ft

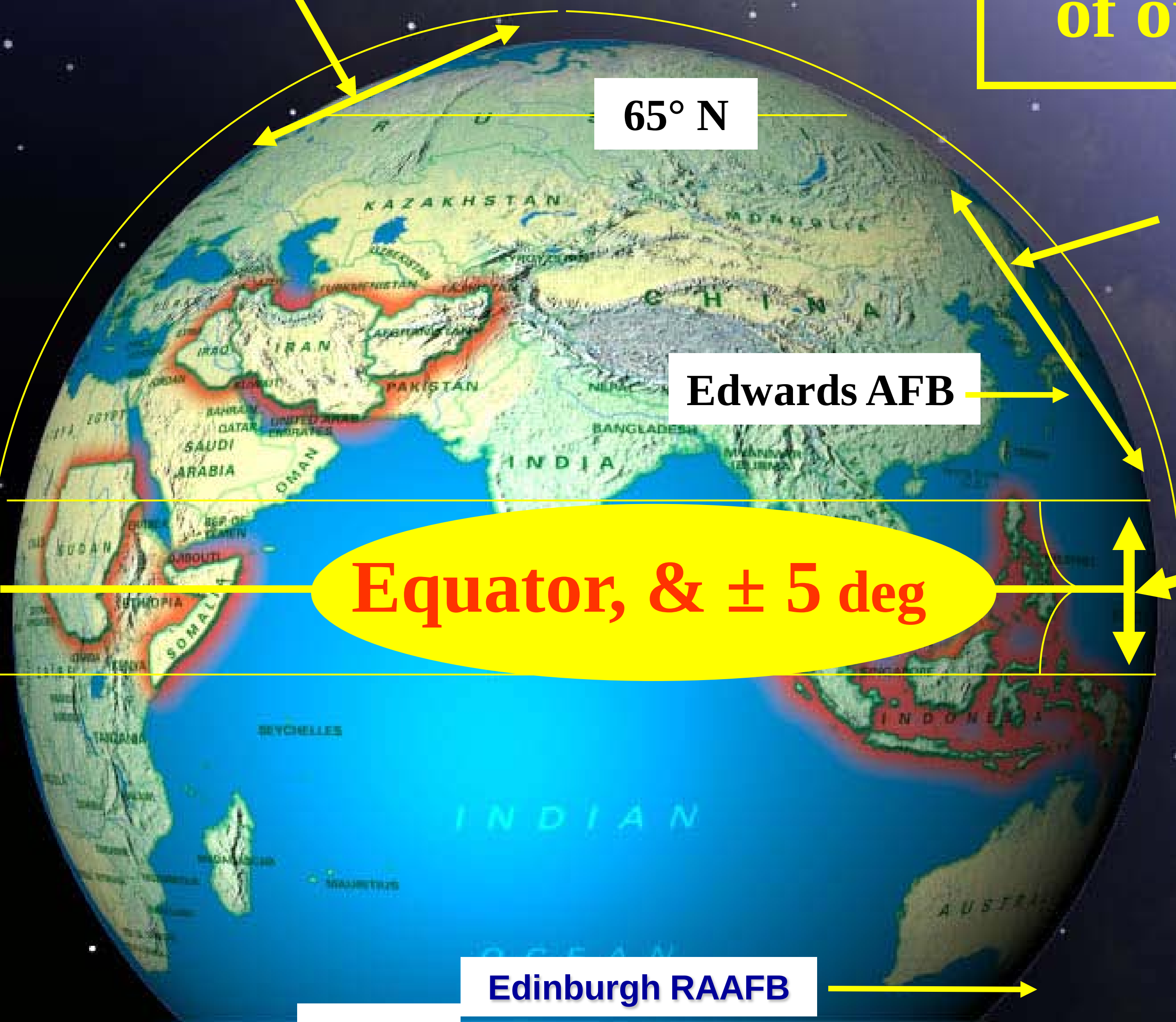
- Atmospheres -

Hydrostatic nature of our atmosphere

Cold at surface = cold at altitude
Warm at surface = warm at altitude

Temperate at surface = temperate at altitude

Hot at surface = Cold at altitude



A Real-world Turbulence Event

- Date: January 22, 1999
- Time: 17:22Z
- Location: 36.126° N Latitude, 118.007° W Longitude
- Altitude: 55,000 ft
- **Event Description:** Over a period of 30 seconds the aircraft experienced a Mach Number increase from 0.60 to 0.65 before the control system compensated for the speed change. Altitude rate, during the event, varied between +3,000 fpm and -1,000 fpm. Maximum load factor attained was 1.25 g's.
- **Mission Summary:** Excluding the turbulence event the aircraft experienced altitude rate variations from +2,000 fpm to -2,000 fpm and load factor varied from +0.6 g to 1.3 g during the cruise climb. Mach Number varied between 0.57 and 0.63.

Turbulence Event Data

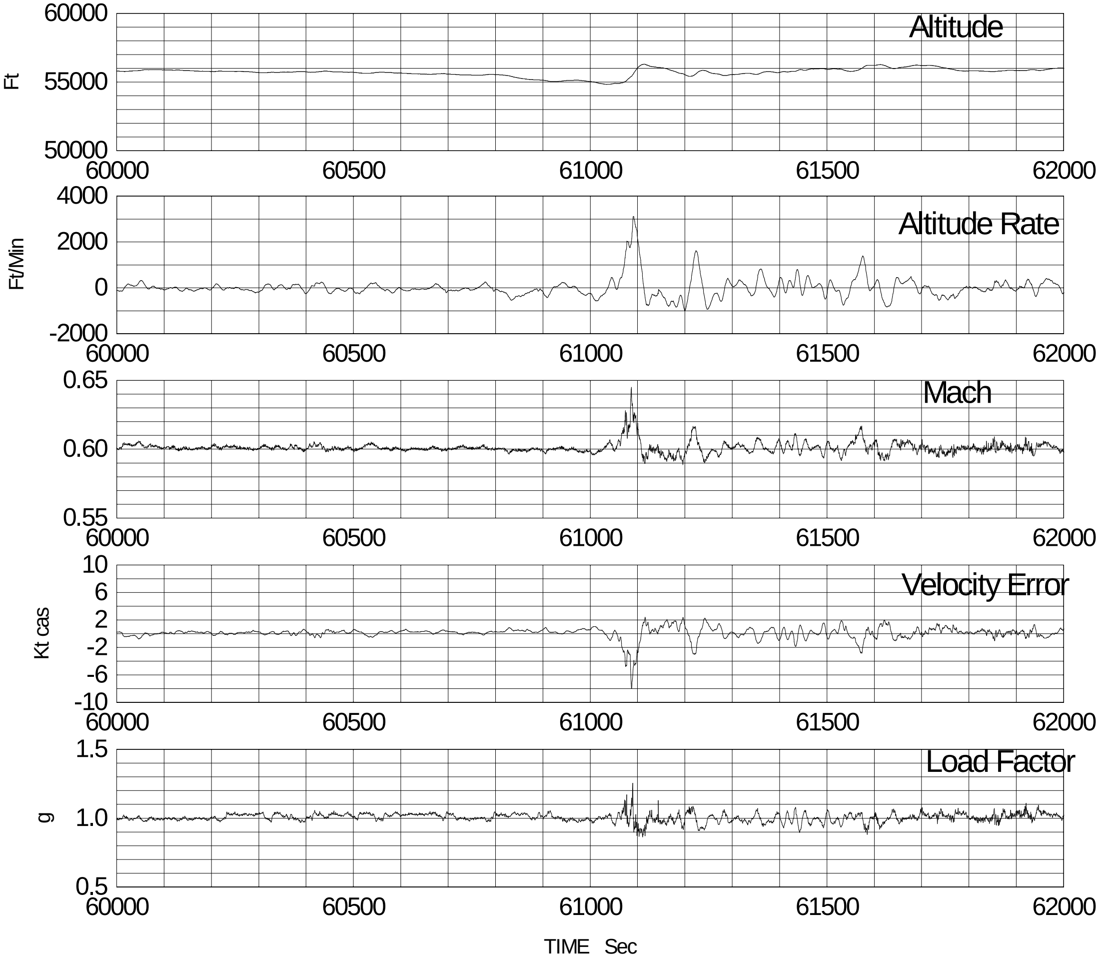
Altitude

Altitude Rate

Mach No.

Airspeed Error

Load Factor



Turbulence Event Conclusions

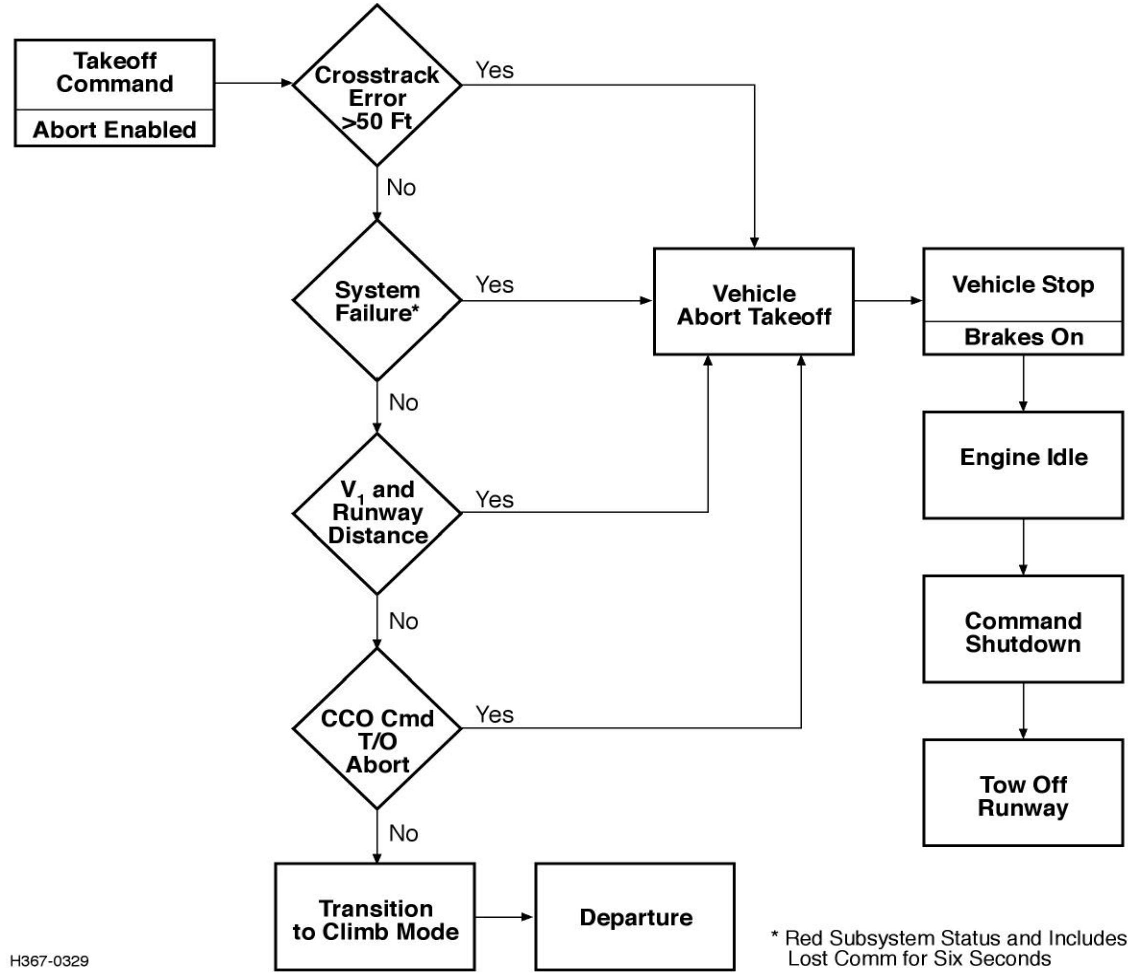
- ***There is correlation between turbulence experienced and the NRL Mountain Wave Forecast Model***

- ***Mountain wave turbulence does not fit standard definitions for Light, Moderate and Severe turbulence levels***
  - — Standard turbulence level definitions are based on high frequency turbulence
  - — MIL-F-8785C Dryden turbulence is high frequency (~short period) in nature and does not represent high altitude mountain wave turbulence experienced to date
  - — High altitude mountain wave turbulence is considered low frequency (~phugoid) in nature and is characterized by variations in altitude, altitude rate, pitch attitude and Mach Number

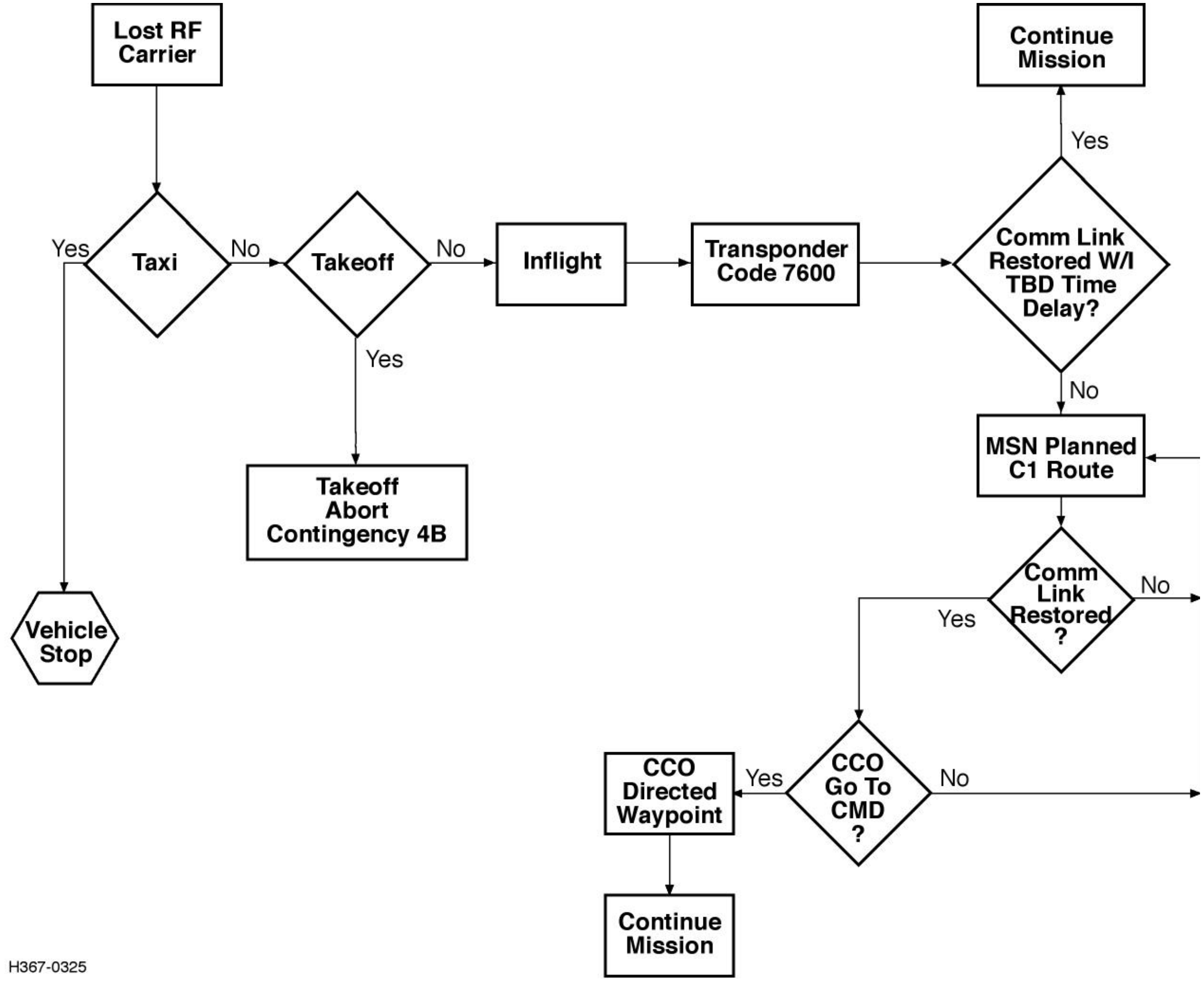
Turbulence Event Conclusions

- ***Flight control system is tolerant to significant high altitude atmospheric disturbances***
  - Airspeed is King. Aircraft controls to calibrated airspeed schedule. Altitude is NOT controlled during cruise climb. Aircraft does not respond directly to Mach variations or altitude variations.
  - Flight control laws were improved to respond faster to airspeed variations resulting in smaller Mach Number transients and larger altitude & altitude rate variations
    No evidence of roll or yaw control issues to date

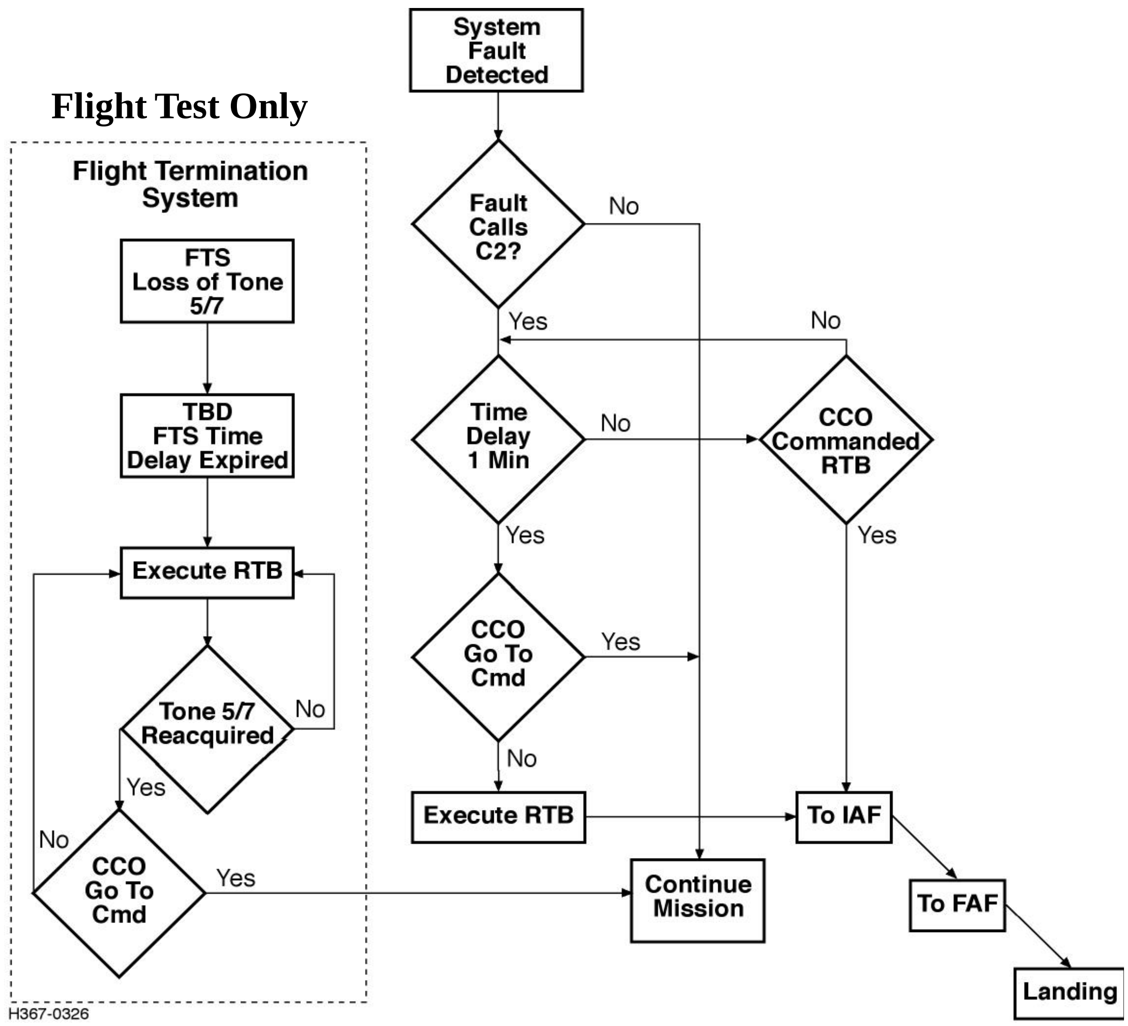
Abort Takeoff Logic Tree, Auto or Pilot Commanded



Typical Fault Logic, Lost Carrier

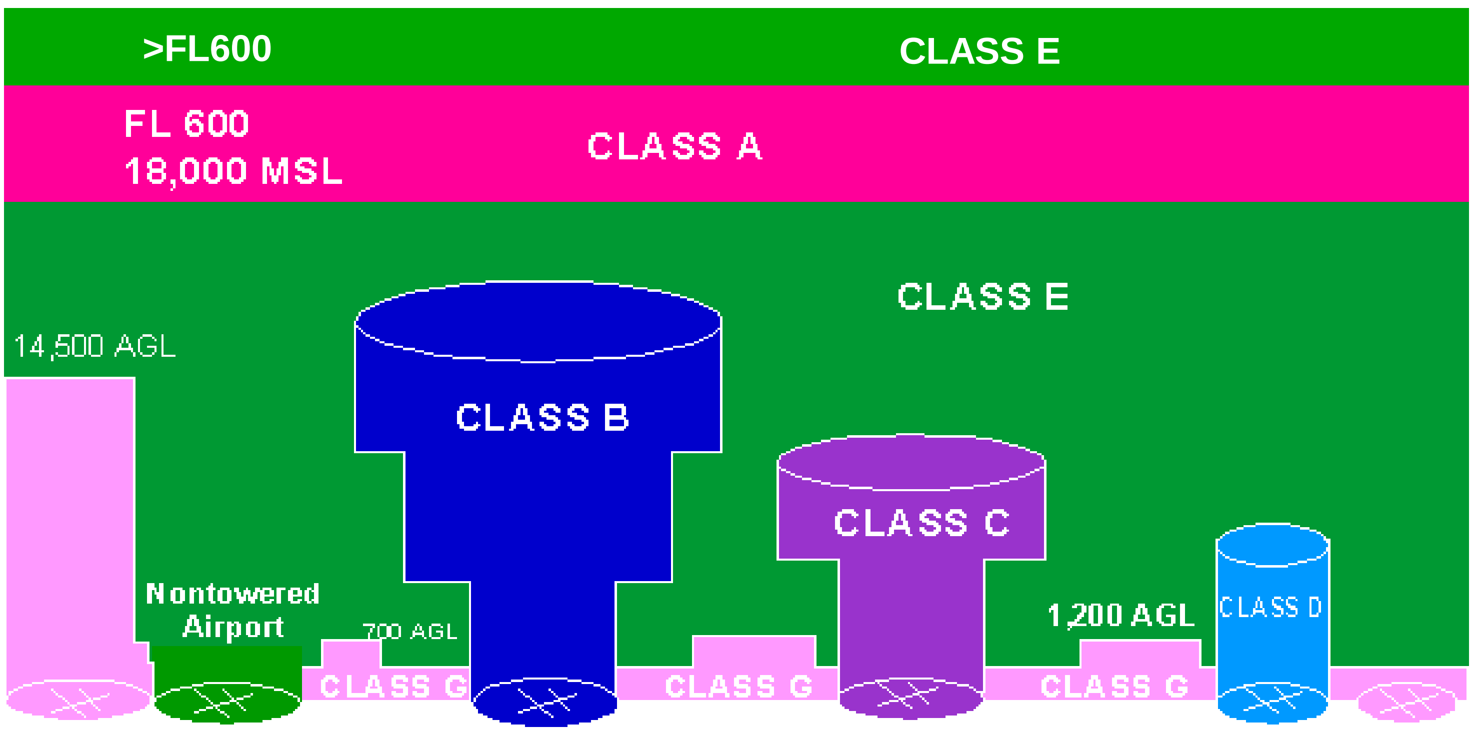


Typical RTB Logic, Autonomous or Commanded

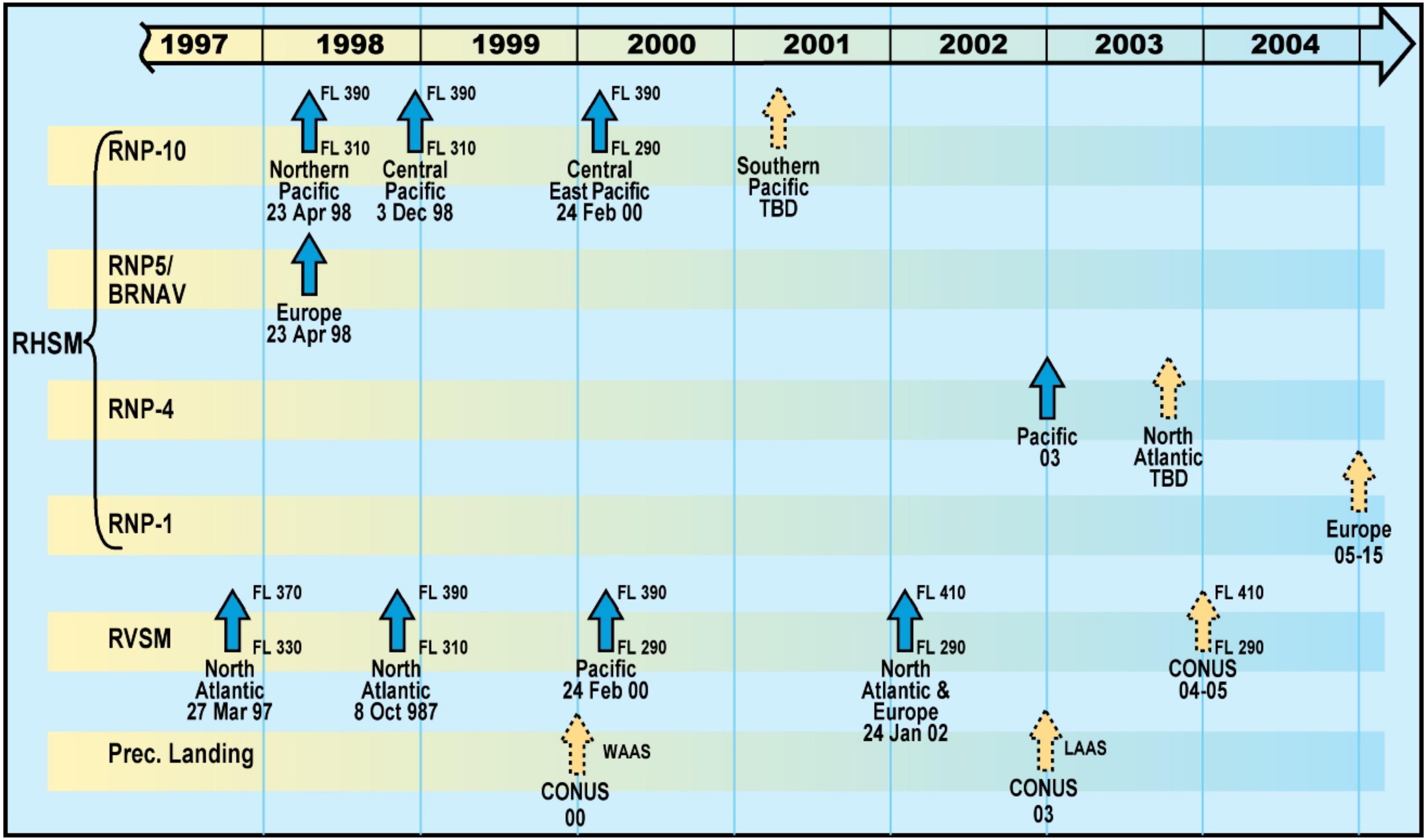


Airspace Coordination Requirements

- Controlled Airspace: Class A, B, C, D, E and F (International)
- Uncontrolled Airspace: Class G
- Special Use Airspace: Prohibited, Restricted, Warning, Alert and Military Operations Areas



Civil Navigation Requirements



Civil Surveillance Requirements