Space Ground Systems: Let's Have More Fun !

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20 Mar 2013

“It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair, we had everything before us, we had nothing before us, we were all going direct to Heaven, we were all going direct the other way”

Charles Dickens

A Tale of Two Cities

- No absence of challenges
  - Budget reductions and belt tightening
  - Competing for talent with other web oriented businesses
  - Information security threats
  - Users who are accustomed to consumer electronics and services
  - The continuing challenge of providing high integrity, high reliability operations

This is a difficult time for ground systems providers

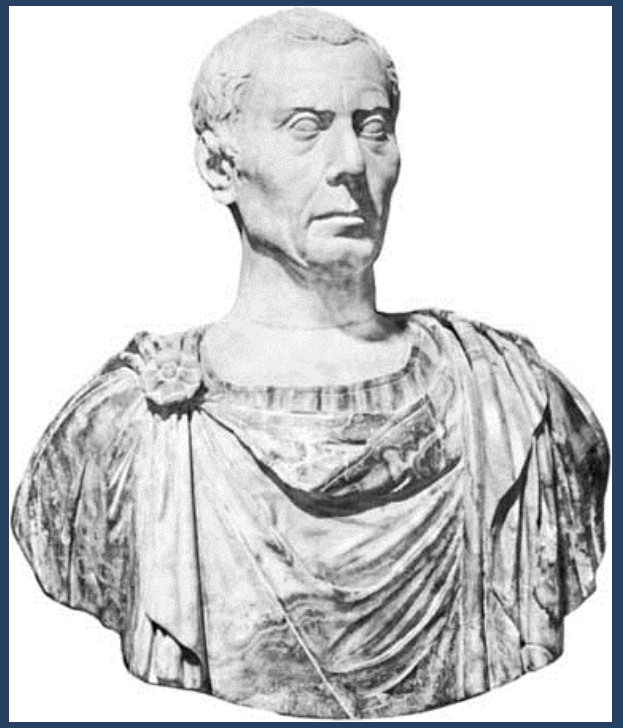
- We get to work with computers, launch vehicles and spacecraft – how cool is that ?
- We have the best tools and technologies for doing our job that we ever have
- We have an industrial base that is generating new tools and technologies at an incredible rate
- The internet provides a low cost worldwide information distribution infrastructure
- There is an opportunity for ground systems developers to provide new services and technologies that revolutionize our businesses

However this is also the best of times

So the big question is “Why can’t we have more fun ?”

- I’ve been involved with a number of ground systems organizations in the past where we were faced with similar challenges
- The purpose of this talk is to explain how we changed what we were doing to provide revolutionary new capabilities and have more fun doing it
  - New Shuttle and Station Mission Control Center
  - X-38
  - University of Tennessee Space Institute airborne science systems
  - SpaceX
- I would submit that in most cases, the things that are limiting our organization’s capabilities and fun are mostly rules that we put on ourselves
- I have found this to be true in government and academia
- Most recently, at SpaceX, we are having a lot of fun challenging the way we do business and building revolutionary capabilities
  - SpaceX had figured this out long before I arrived there but I could immediately recognize common themes with other projects I’ve been involved with

The fault, dear Brutus, is not in our stars,
But in ourselves, that we are underlings."
Shakespeare, in *Julius Caesar* (Act I, Sc. II)



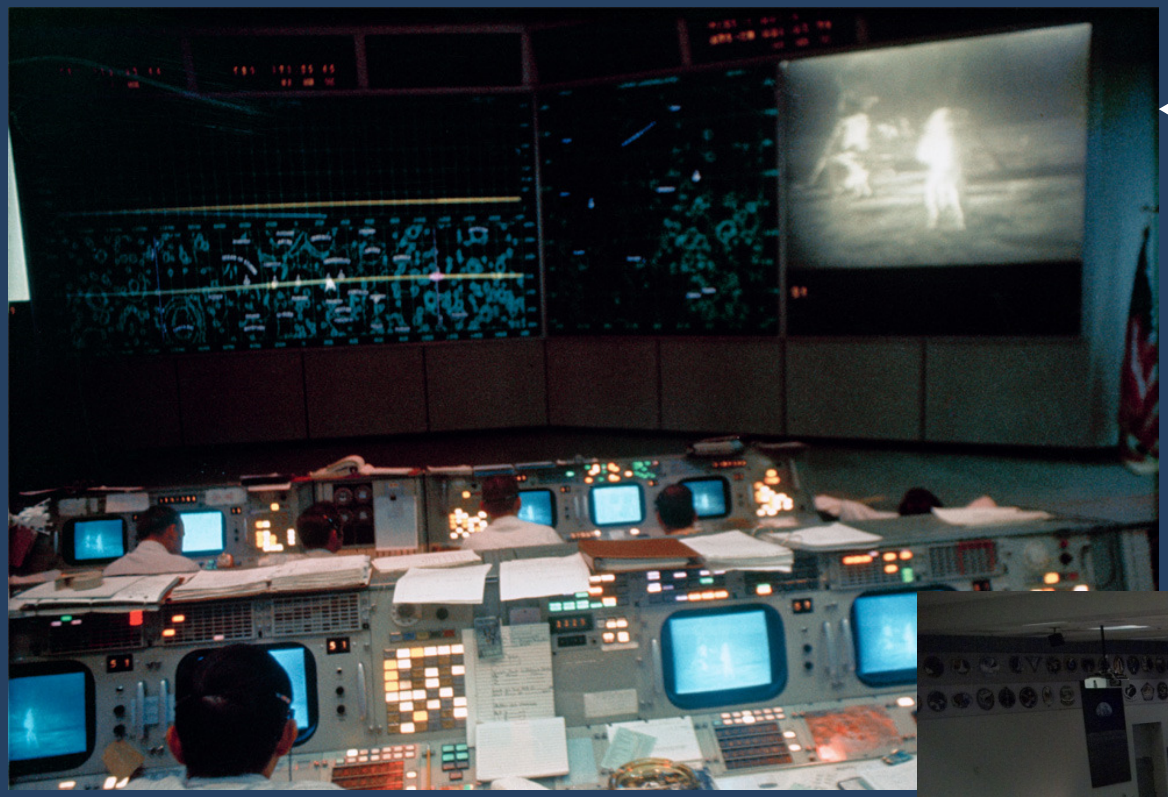
Caveat Emptor

- In this presentation, I'm going to make some generalizations
  - May not apply to your particular situation
  - This is not a one size fits all kind of business
- But hopefully, this will provide the seed for new thinking

Some ideas to unlock potential

- Why can't we use more Open Source/shareware/freeware ?
  - Shareware and freeware from legitimate sources may have more test time by an informed and active community than we can afford to generate ourselves
  - Gain greater functionality faster
  - Have to be careful about picking versions and screening for security problems – only established foundries
- Why can't we use more against commercial hardware and software ?
  - Smart use of COTS can focus us on the unique aspects of our problem domains
- Why can't we segregate information to allow newer tools- greater connectivity ?
  - Understanding that there are issues with security and information assurance
  - Connection is the future
- Can we eliminate bias against higher level tools – LabVIEW, Matlab, Excel, WinPlot, TecPlot etc…?
  - Should be using everyday engineering tools in the control center
- Can we give users greater control to gain greater user synergy ?
  - In my experience, a better solution can usually be found by allowing the users of a system more involvement in its definition
- Can we cross organization lines- using the same systems in factory, hangar, prelaunch and mission ?
  - Tremendous synergy from re-use, eliminating unique systems, allowing lessons learned in one phase of the life cycle to be shared in all phases
- Can we challenge extreme performance requirements that drive custom solutions ?
  - In my experience, extreme performance requirements that drive a complex custom solution are rarely valid
  - Usually these can be challenged or modified

Mission Control Center Upgrade – NASA Johnson Space Cen ter , Houston Texas - 1995



Old Mission Control – Circa 1969
Was still fundamentally this way in 1993

New Mission Control 1995-present

The story

Flight Director emblem

- In December 1993 I was one of the NASA Flight Directors working on the Hubble Repair Mission
- John O'Neill, Director of Mission Operations came to my console and informed me "This is going to be your last flight as a Flight Director"
- Astonished, I asked "Did I screw up ?"
- He responded "No, we need you to build the next generation control center. And do it fast"

John O'Neill

Hubble Repair

My Flight Control Team

The crisis

- Space Shuttle was in full swing in 1993
- NASA was gearing up for ISS assembly. The program had undergone several redesigns to reduce cost
- A Shuttle Mission Control Center Upgrade project had been underway since 1983 – 10 years and over $100M had been spent
- A new ISS control center building had been built – adjacent to but completely disconnected from the Shuttle MCC
- The two control center projects had some common elements (front end processing) but were otherwise different
- Both programs were frustrated with total costs to complete
- The ISS control center schedule showed that it would barely meet the ISS first launch scheduled for 1996 (actually happened in 1998)

- **ISS program stated that if JSC Mission Operations couldn't reduce costs to develop and operate the control center that it would run all of its initial operations out of Moscow**

“You never let a serious crisis go to waste. And what I mean by that it's an opportunity to do things you think you could not do before.”

Rahm Emanuel

- There was open warfare between the operators and the developers
  - Operators were so frustrated with 6 month to one year lags to develop new computations that they were “rolling their own” in offline computers
  - New mission opportunities were being lost because the data system costs were too high
  - Mission Control Center upgrade had been going on so long without real benefit that faith had been lost
- The developers were locked in a mainframe based architecture
  - Shuttle was still using black and white text displays, background graphics only except for a few highly specialized abort displays
  - Shuttle flight controllers were still monitoring the shuttle flight computers by looking at data in Hex although all the systems displays were calibrated
- I had a leg in both communities
  - I had been a flight controller and flight director
  - I had run some prototype projects placing workstations in the control center

The problems

- The Real Time Data System (RTDS) was a small project to insert UNIX (gasp) workstations programmed by flight controllers (the horror) in parallel with the mainframe system
- RTDS provided color and graphics as well as rule based automation
- System had its own COTS based telemetry front end
- System had been in operations from 1988-1993 operating on shoestring budgets

Our training ground

The approach

- Join the two control centers in a common solution
- Give users direct control over the resources that were building the applications (The Nifty Fifty)
- Build a common set of solid workstation services that would enable users to establish a minimum capability
- Build APIs that allowed user developed applications to directly connect to telemetry and trajectory data
- Build a test, library and simulation environment that allowed users to test in a professional manner
- Embrace COTS hardware and software – Eliminate custom solutions
- Build on Open standards – Unix, TCP/IP, FDDI then Ethernet
- Run in parallel to prove concept , then orbit first, then entry, then ascent
- Test a little, fix a little approach
- Multiple rapid spirals

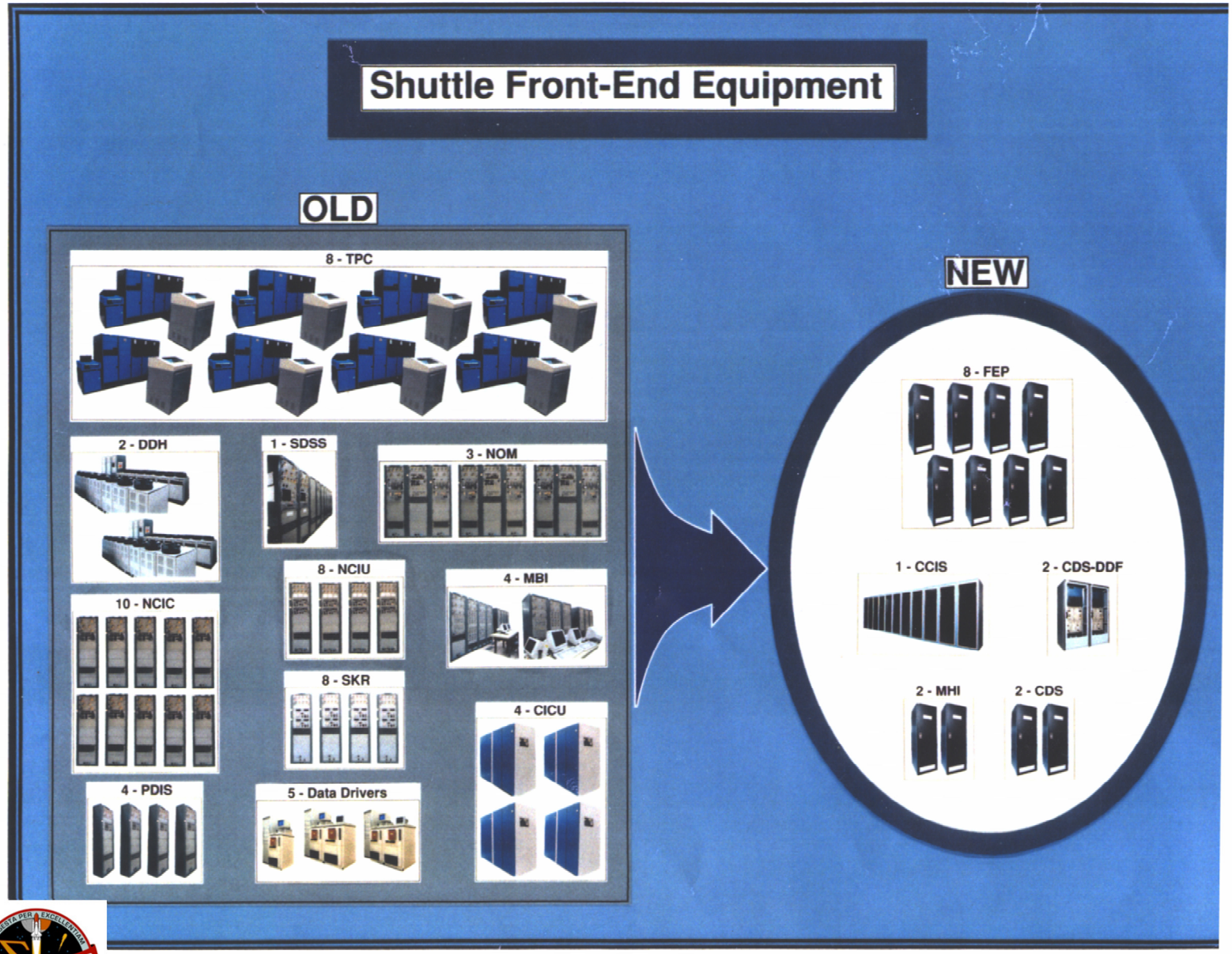
- JSC Center Director got anonymous calls about the MCC being destroyed
- Anonymous Safety Reports were filed that we had to answer
- The Inspector General planted a team in my organization for 6 months
- Our first shuttle ascent sim was a total disaster and received a 4 page scathing memo from my former comrades in the flight director office

- Anxiety all the way up the management chain but they backed us up
- We knew what we were doing and stuck to our guns

This was highly controversial

The result

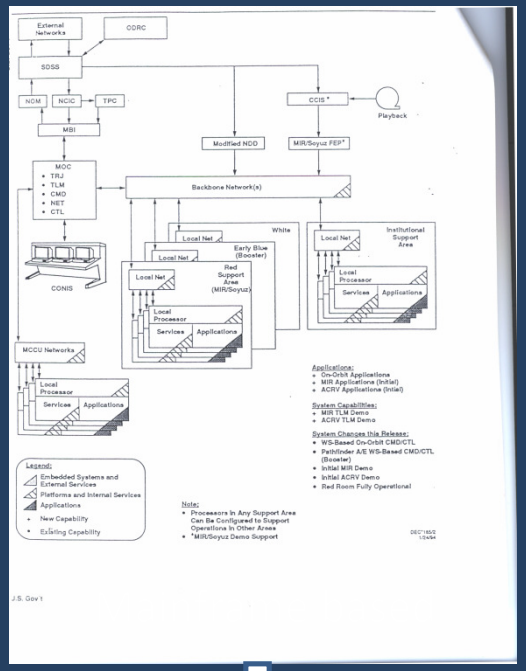
- Control center development cost reduced by $75M
- Control center operational in 18 months, had significant flight operations experience before ISS first launch
- Controllers easily transition between Shuttle and ISS tasks
- No major issues in any flight operation
- For the 11 years of ISS operations, NASA has run the Mission Control Center for shuttle and station for less than the amount necessary to run shuttle alone before the upgrade
- The hardware and software has been upgraded twice using the same architecture and software base
  - Transitioned from high end workstations to PCs
  - 100 Mbit FDDI transitioned to Ethernet
  - Last upgrade replaced all of the user workstations for less than $4M
- The contractors working with us, who initially opposed the approach, wound up selling the solution to multiple customers



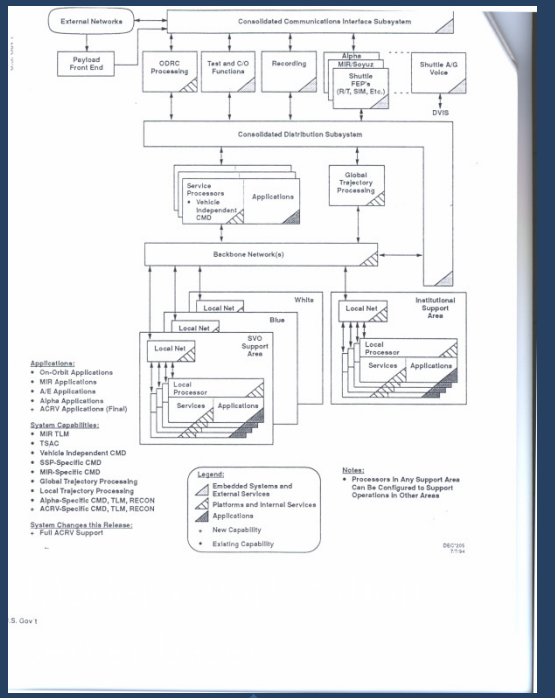
Reduction from 1400 racks (shuttle only) to 700 racks (shuttle and station combined)

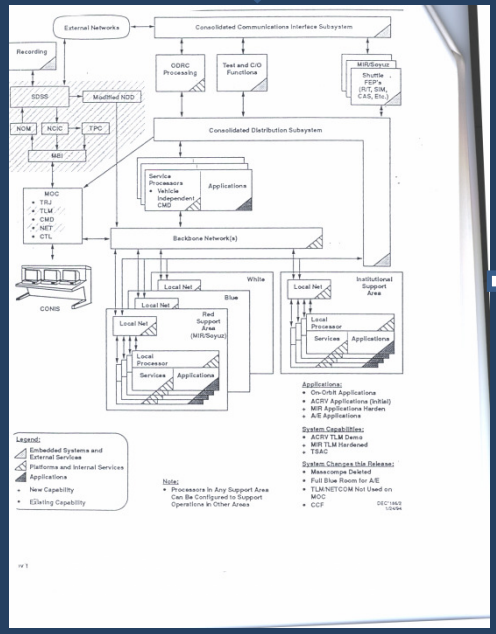
Board level maintenance in old control center

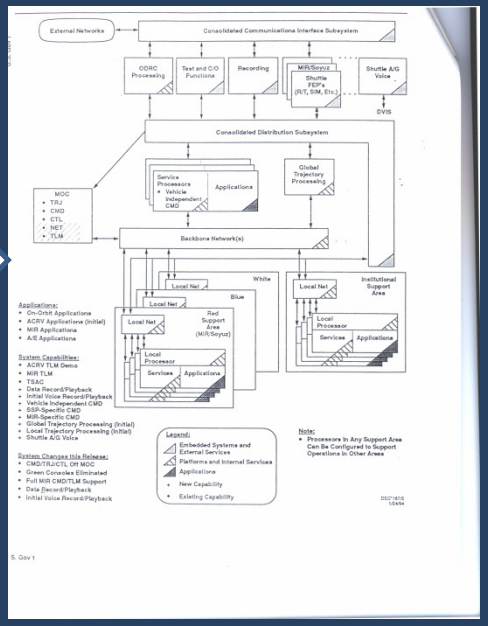
Workstation level maintenance in new control center

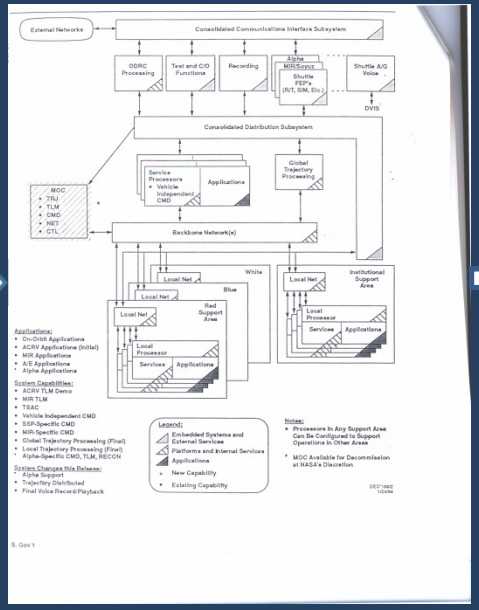


- 4 Rapid Spirals in 18 months
- No requirements documents
- No formal traceability to other program documents
  - We knew what needed to be done – process and display telemetry, issue commands
- Capability description diagrams
- Document as built design
- Extensive testing









We even got an article about the effort in Rolling Stones Magazine

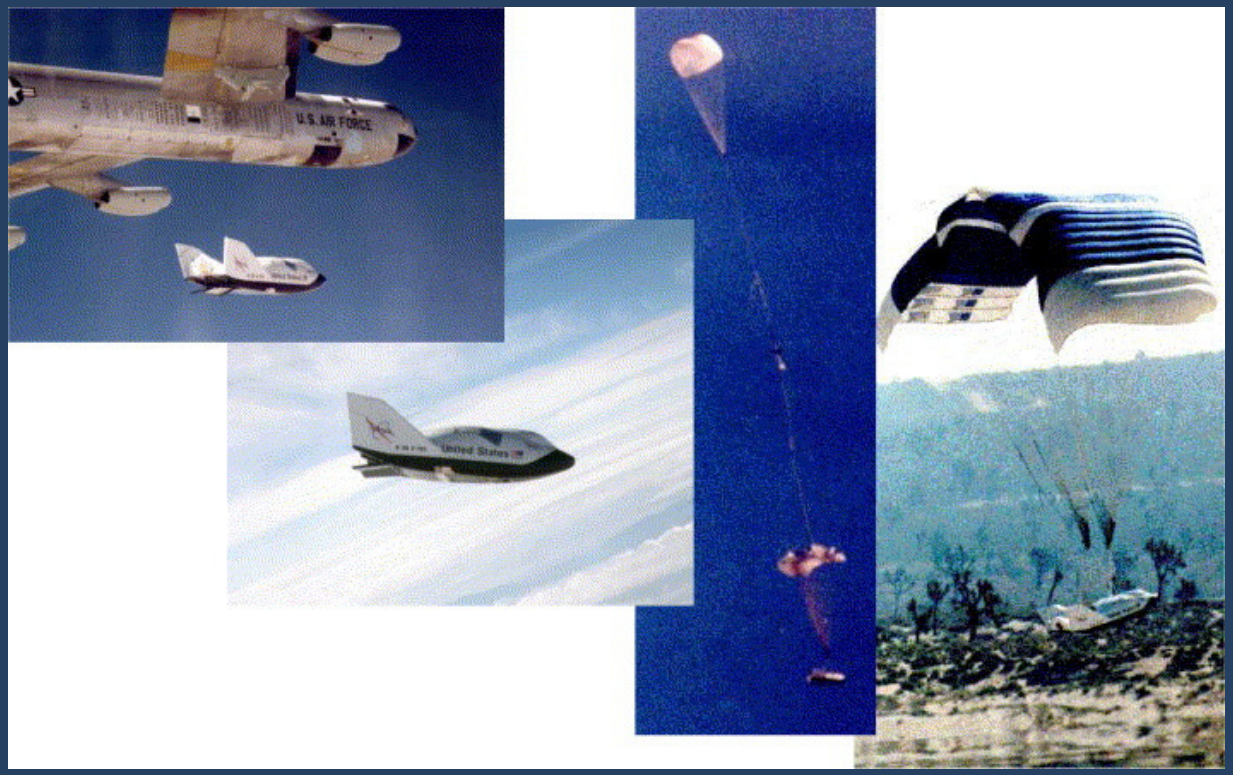
X-38 Crew Return Vehicle Prototype

- Prototype lifeboat/ambulance for the International Space Station
- Flew 8 drop flights from B-52, intercepting orbital return trajectory
  - Flew as a lifting body then transitioned to parafoil flight for final descent and landing
  - Worlds largest parafoil (7500 sq ft – 50% more wing area than a Boeing 747)
    - 40 guided parafoil test drops
- Space vehicle built and was being readied for flight when program cancelled in 2002 – Cape shipment was in sight
- 7 year program full cost accounted cost less than $330M total

Dryden Flight Research Center EC99 45080-25 Photographed 09JUL1999
The X-38 Ship 2, Crew Return Vehicle is released from the B-52 Mothership.
NASA/Dryden Carla Thomas

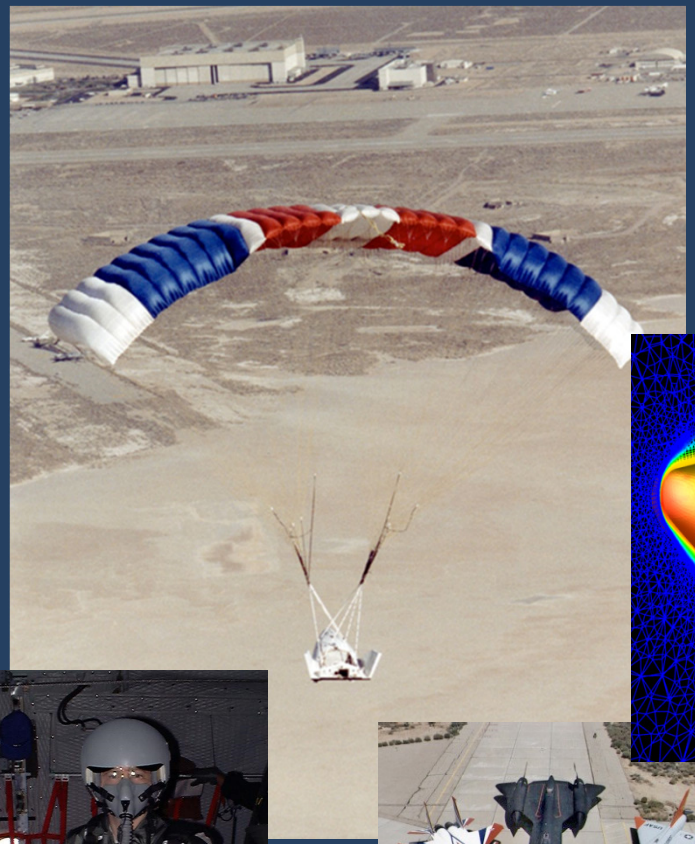
Space Test Vehicle

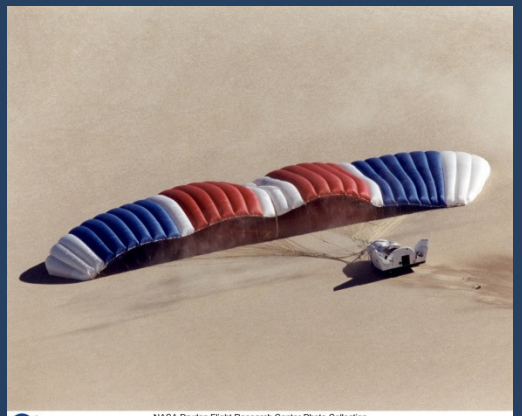
X-38 Mission Profile



- Dropped from 50,000 feet, 14 Miles from Target
- 25,000 lbs, 35 feet long
- Vehicle in Transonic flight – Navigated by inertial GPS, flight controlled by surfaces and electromechanical actuators
- Drogue deployed to slow vehicle and extract/deploy parafoil at 15,000 feet
- 7500 sq foot parafoil
- Landed within 150 feet of intended spot, using winches to pull on control lines to steer parafoil. Using wind estimate from inertial/gps, steered into wind and flared using laser altimeter to determine altitude. Touchdown velocity less than 35 mph, descent velocity less than 15 fps

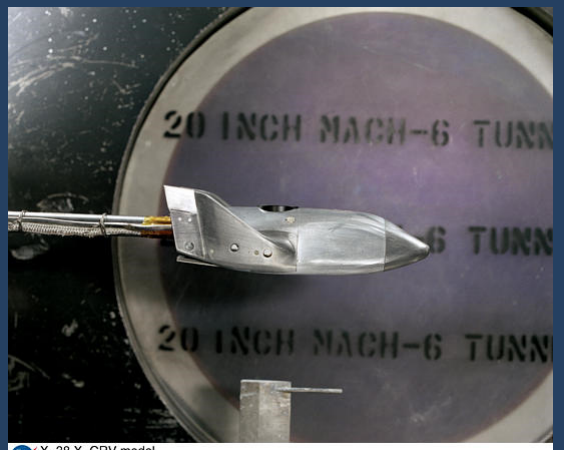
X-38 Images



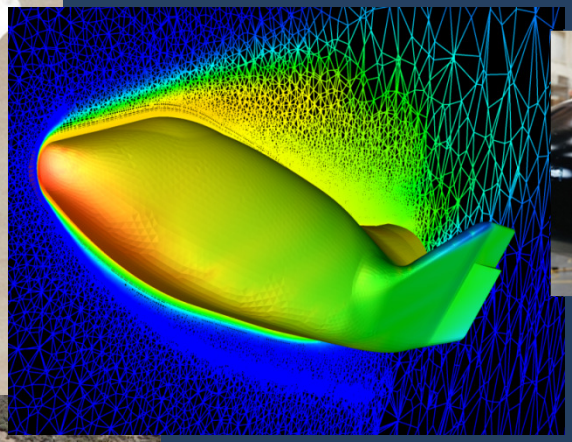


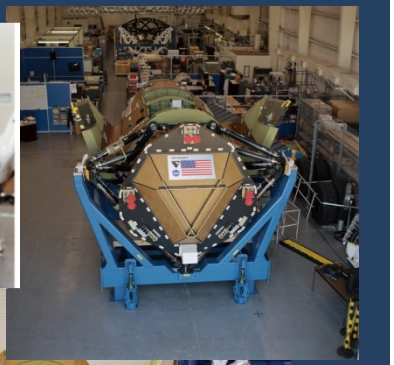
NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC00-0317-52 Date: November 2, 2000 Photo by: Carla Thomas

The world's largest parafoil slowly deflates after carrying the X-38, V-131R, to a safe landing



X-38 X-CRV model
NASA Langley Research Center 7/14/1998 Image # EL-1998-00153

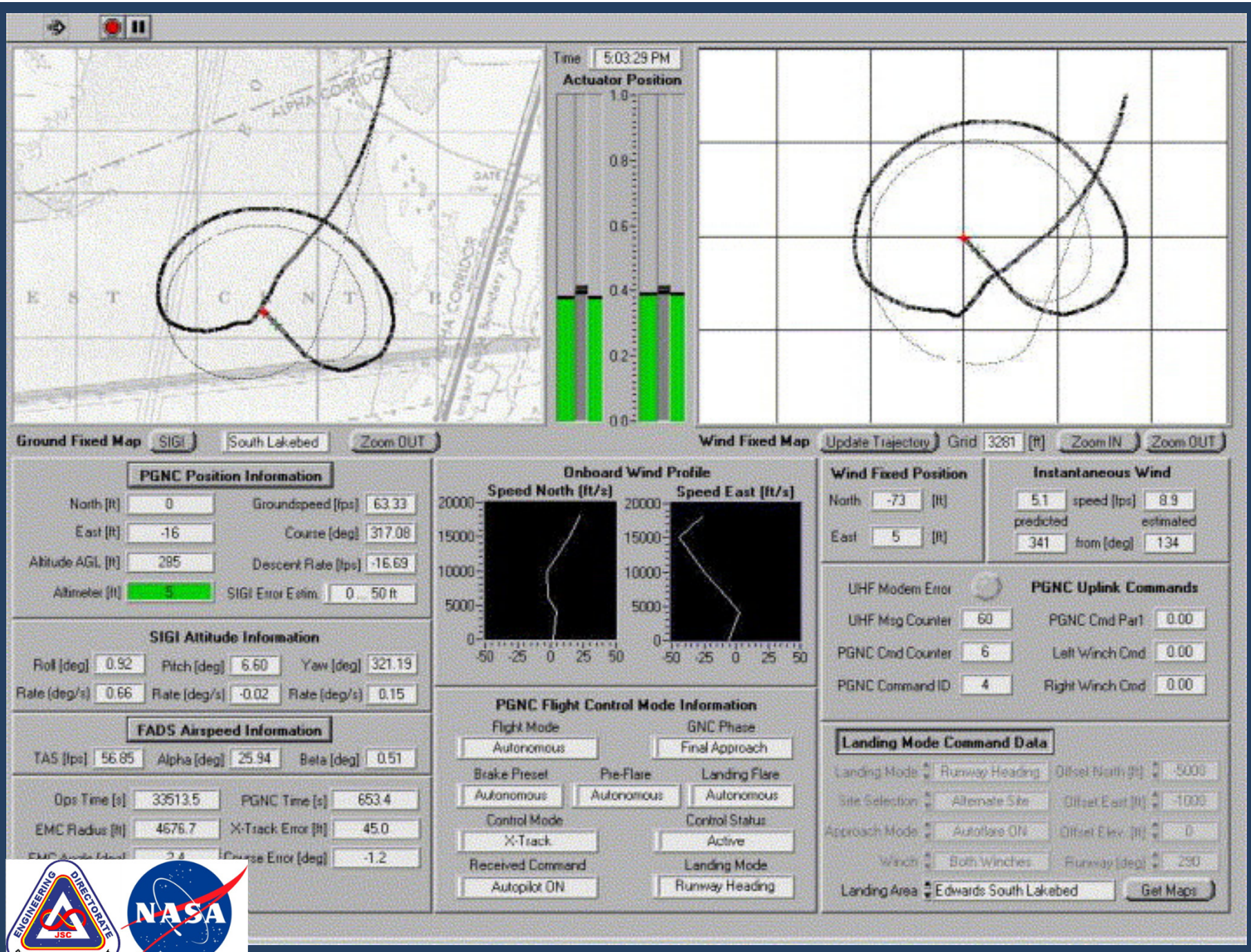




NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC97-44165-149 Date: July 16, 1997 Photo by: Tony Landis
1997 Research Aircraft Fleet on Ramp - X-31, F-15 ACTIVE, SR-71, F-106, F-16XL Ship #2, X-38, Radio Controlled Mothership and X-36

X-38

- One data system cradle to grave
  - Same control/display system used on the assembly floor in Houston, in the hangar at Dryden, in the control center at Dryden and on the B-52
- LabVIEW based, PC Based, Ethernet based
- Remote operation
  - Left most of our team in Houston. System managed from Houston.
- Very small development team
- Users heavily involved in applications


Time 5:03:29 PM
Actuator Position
1.0
0.8
0.6
0.4
0.2
0.0
Ground Fixed Map
SIGI
South Lakebed
Zoom OUT
Wind Fixed Map
Update Trajectory
Grid 3281 [ft]
Zoom IN
Zoom OUT
PGNC Position Information
North [ft] 0
East [ft] -16
Altitude AGL [ft] 285
Altimeter [ft] 5
Groundspeed [fps] 63.33
Course [deg] 317.08
Descent Rate [fps] -16.69
SIGI Error Estim 0 .. 50 ft
SIGI Attitude Information
Roll [deg] 0.92
Pitch [deg] 6.60
Yaw [deg] 321.19
Rate (deg/s) 0.66
Rate [deg/s] -0.02
Rate (deg/s) 0.15
FADS Airspeed Information
TAS [fps] 56.85
Alpha [deg] 25.94
Beta [deg] 0.51
Ops Time [s] 33513.5
PGNC Time [s] 653.4
EMC Radius [ft] 4676.7
X-Track Error [ft] 45.0
Course Error [deg] -1.2
Onboard Wind Profile
Speed North [ft/s]
Speed East [ft/s]
20000
15000
10000
5000
0
-50 -25 0 25 50
PGNC Flight Control Mode Information
Flight Mode
Autonomous
GNC Phase
Final Approach
Brake Preset
Autonomous
Pre-Flare
Autonomous
Landing Flare
Autonomous
Control Mode
X-Track
Control Status
Active
Received Command
Autopilot ON
Landing Mode
Runway Heading
Wind Fixed Position
North -73 [ft]
East 5 [ft]
Instantaneous Wind
5.1 speed [fps] 8.9
predicted estimated
341 from [deg] 134
UHF Modem Error
UHF Msg Counter 60
PGNC Cmd Counter 6
PGNC Command ID 4
PGNC Uplink Commands
PGNC Cmd Par1 0.00
Left Winch Cmd 0.00
Right Winch Cmd 0.00
Landing Mode Command Data
Landing Mode Runway Heading
Site Selection Alternate Site
Approach Mode Autoflare ON
Winch Both Winches
Offset North [ft] -5000
Offset East [ft] -1000
Offset Elev [ft] 0
Runway [deg] 290
Landing Area Edwards South Lakebed
Get Maps

Old aircraft data system

New aircraft data system

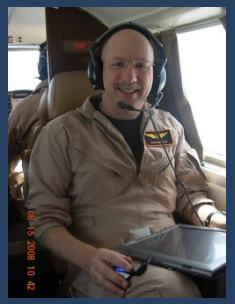
- Installed and run in parallel initially
- Multiple Rapid Spirals
- Replaced fixed gauges with Samsung 7 inch Ultra Mobile PC
- LabVIEW based
- COTS data acquisition front end
- All data logged in user friendly format
- Used in simulation lab as well as flight

UTSI is one of only three universities teaching flight testing in the US and the only public university that offers a masters in flight test engineering

Data display on iPhone

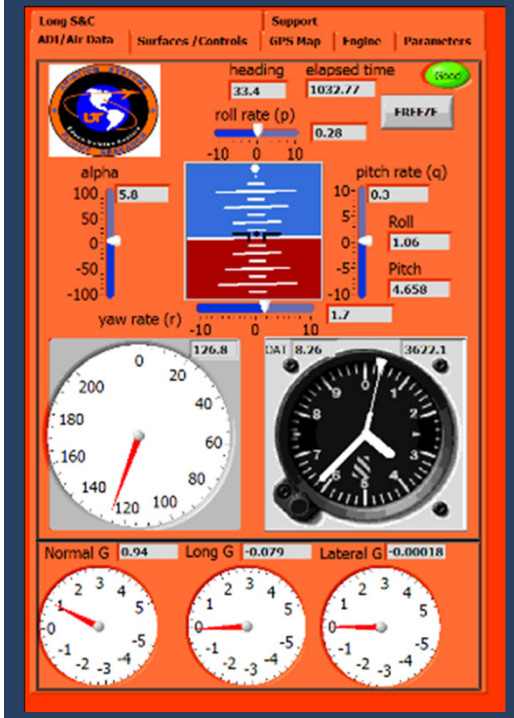
Sim Lab Use of New Data Displays

University of Tennessee Space Institute (UTSI) 2007-2011



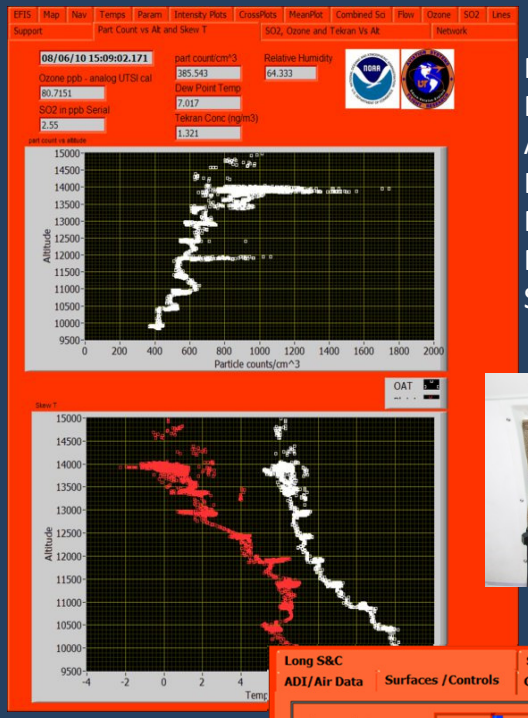
Space Institute

AVIATION SYSTEMS FLIGHT RESEARCH Educo-Volatus-Exploro

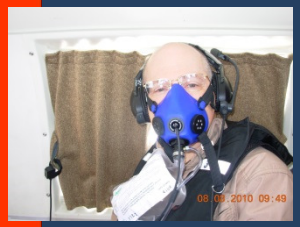


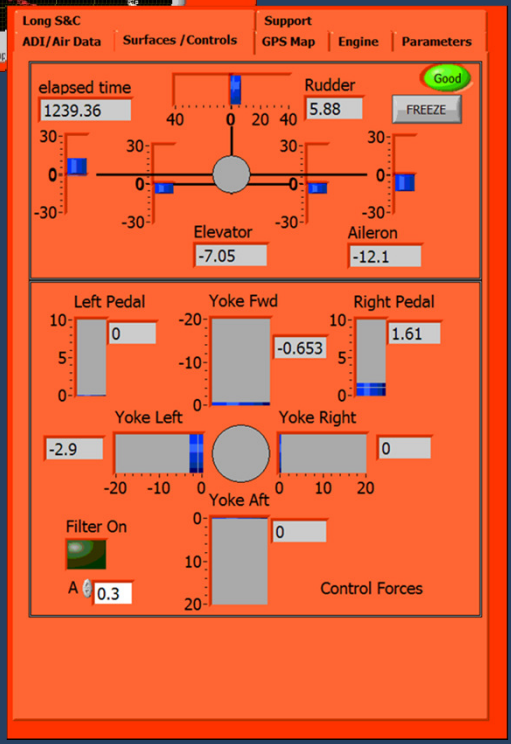
Standard Flight Instruments

Real Time Plots of Dynamic Maneuvers



Real Time Plotting of Atmospheric Humidity and Particulates for NOAA Airborne Science Mission





Visualization of Surface and Controls Positions

Typical LabVIEW inflight displays

The SpaceX Story

- Founded in 2002 by Elon Musk
- Committed to providing the safest, most reliable and economical access to space
- Highly efficient and vertically integrated—value-wise, SpaceX manufactures over 70% of the Falcon 9 launch vehicle in-house to control quality, cost and schedule

Chantilly, VA

Washington, D.C.

Hawthorne (Los Angeles) Headquarters

Central Texas

SLC-40, Cape Canaveral

SLC-4E, Vandenberg

SpaceX Flight History

Powered by Merlin ablatively cooled engine

Powered by Merlin regeneratively cooled engine

Falcon 1 Demo 1 Mar 24, 2006

Falcon 1 Demo 2 Mar 20, 2007

Falcon 1 Flight 3 Aug 2, 2008

Falcon 1 Flight 4 Sep 28, 2008

Falcon 1 RazakSAT Jul 14, 2009

Falcon 9 First Flight Jun 4, 2010

Falcon 9 Flight 2 Dragon COTS C1 Dec, 8 2010

Falcon 9 Flight 3 Dragon COTS 2+ May 22, 2012

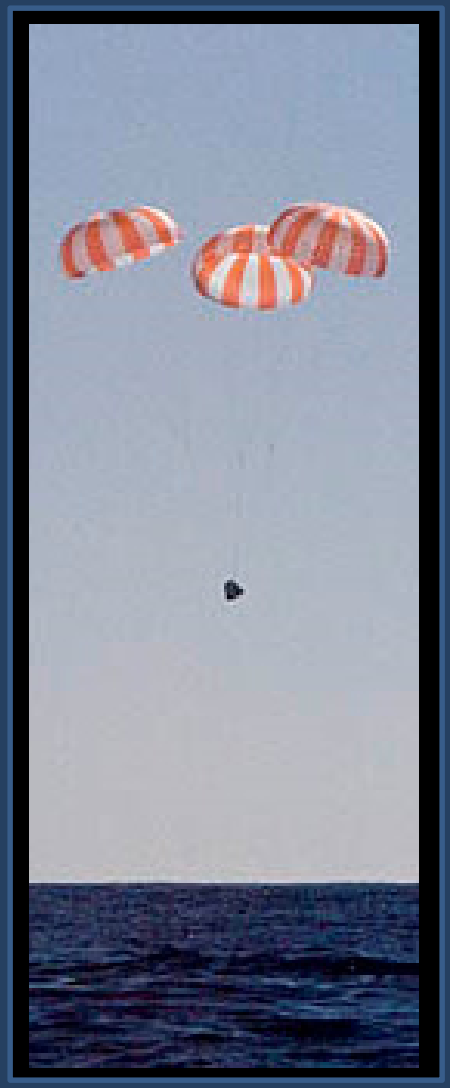
Falcon 9 Flight 4 Dragon CRS-1 Oct 7, 2012

Falcon 9 Flight 5 Dragon CRS-2 Mar 1,2013

SpaceX Accomplishments

In our first 11 years, SpaceX has…

- Designed, developed and qualified the world's lowest cost orbital launch system – Falcon 1
- Designed and developed a completely new intermediate orbital launch system – Falcon 9
- Become the first commercial company in history to re-enter and recover a spacecraft from Earth orbit
- Delivered cargo to the International Space Station under the COTS and CRS contracts—another commercial first
- Secured over $3.0 Billion worth of business (currently over 40 missions)

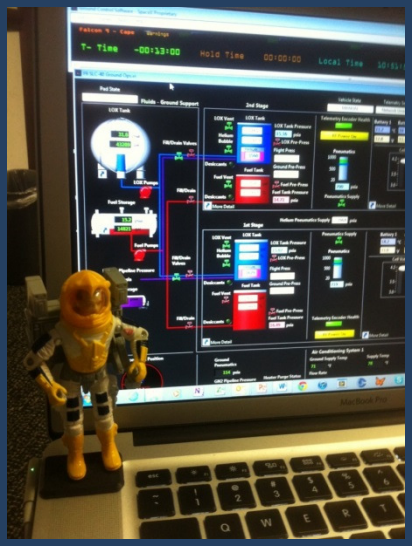


Keys to Success

- **Design** – Increase reliability and decrease cost through simplicity, redundancy and robust design margins
- **Evolutionary approach** – Leverage commonality between vehicles
- **Development and operations** – Encourage rapid prototyping in the development phase, and stringent quality control in the production phase
- **Distributed Systems Engineering Model** – System level responsibilities explicitly distributed in departments with networks of integrators ensuring system level problem solving
- **In House Manufacturing** – Over 70% of rocket dry mass is manufactured in-house from raw materials

SpaceX Launch Control – Cape Canaveral

Hawthorne Mission Control



Running Displays on Laptop

LabVIEW based - 2 orders of magnitude less equipment than the New MCC in Houston – PC and Server based

SpaceX Ground Systems take advantage of the internet to bring expertise to bear

- During the first flight of the Dragon to ISS , a question came up about cargo operations
- The mission director mused on the loop “I wish we could get Jason to look at this”
- One of the operators used Instant Messaging to contact Jason.
- He responded and was asked to come up on the loop
- A minute or so later, Jason was talking on the loop in the control center to the mission director and assured him that he was looking at the data and everything was ok
- The mission director asked Jason where he was because there was a lot of background noise
- Jason replied that he was on flying back from the Cape and was logged in via the aircraft’s wireless
  - He was logged in and looking at mission data
  - He was using Concert to tie into the voice system

SPACEX

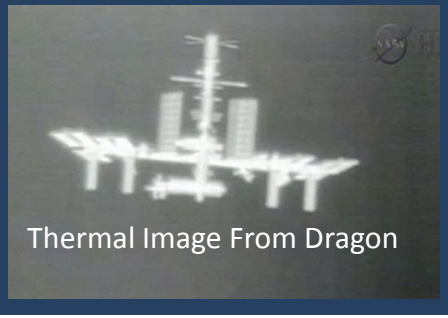
SpaceX ground systems allow us to use all our assets independent of geographic limitations

- During the CRS-1 mission I walked into the control center during attached operations and was surprised to find
  - All the main displays were up
  - No one was logged in at the control center
- Control had been handed over to the Cape control center
- Personnel who normally performed prelaunch checkout were monitoring Dragon on-orbit
  - They had been trained for on-orbit operations as well as emergency departure and entry

SPACEX

SpaceX Ground Systems support the rapid formation of teams to solve problems

- During the first ever approach to the ISS, we ran into some problems with how the sensors were viewing the ISS
- A decision was made to send some commands to the Dragon to adjust sensor processing
- Key players in the discussion
  - Team at The Dragon control center in Hawthorne
  - A Flight Software expert who was located at the Dragon Cape control center
  - Flight software testbed operators in Hawthorne
  - Houston ISS mission control
- All linked up within seconds
  - Command was discussed
  - Command was simulated and tested in our hardware-software testbed
  - Results discussed
  - Command built and sent to the Dragon
  - Rendezvous continued successfully


Thermal Image From Dragon


Dragon During Approach

SPACEX

Conclusions

- There are some common techniques that can be used to introduce new technologies into static environments
- Times of crisis can present opportunities for radical solutions which can bring great rewards
- Is it time to use the current crisis to reach new levels of capability and fun ?

"Do not go where the path may lead, go instead where there is no path and leave a trail"
Ralph Waldo Emerson