Integration and Ruggedization of a Commercially Available Gas Chromatograph and Mass Spectrometer (GCMS) for the Resource Prospector Mission (RPM)

Presentation to HEMS
September , 2013

NASA
KSC
JPL

Inficon
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Presentation Overview

- **Mission Summary**
- **Preliminary Payload Requirements**
- **Analog field tests Engineering Test Unit Design**
- **Challenges (Budget, Intellectual Property, Technical)**
- **Flight Forward Plans**

Resource Prospector Mission (RPM)

RPM is a potential <u>low cost</u> mission to the moon comprising a soft lander, and a rover carrying a payload designed to detect and map volatiles and for demonstration of in situ resource utilization (production of oxygen from regolith). The concept of operations includes landing in an area of limited solar illumination in the vicinity of the lunar south pole where volatiles may be trapped in the sub-surface.

Why do we need a Resource Prospector Mission (RPM)

To maintain a long term human presence in space , we must learn to use the resources that are available and not rely completely on transporting all of our supplies in other words"

We have to learn to "Live off the Land"

Imagine how far Lewis and Clark would have gotten if they had to rely on all the water food and shelter that they packed in.

What is RESOLVE?

Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

RESOLVE is an internationally developed payload (NASA and CSA) that that can perform two important missions for Science and Human Exploration of the Moon

Resource Prospecting Mission: (Polar site)

- ✓ **Verify the existence of and characterize the constituents and distribution of water and other volatiles in lunar polar surface materials**
  - **Map the surface distribution of hydrogen rich materials**
  - **Determine the mineral/chemical properties of polar regolith**
  - **Measure bulk properties & extract core sample from selected sites**
    - To a depth of 1m with minimal loss of volatiles
  - **Heat multiple samples from each core to drive off volatiles for analysis**
    - From <100K to 423 K (150°C)
    - From 0 up to 100 psia (reliably seal in aggressively abrasive lunar environment)
  - **Determine the constituents and quantities of the volatiles extracted**
    - Quantify important volatiles: H_2, He, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S, SO_2
    - Survive limited exposure to HF, HCl, and Hg

ISRU Processing Demonstration Mission: (Equatorial and/or Polar Site)

- ✓ **Demonstrate the Hydrogen Reduction process to extract oxygen from lunar regolith**
  - **Heat sample to reaction temperature**
    - From 423 K (150°C) to 1173 K (900°C)
  - **Flow H_2 through regolith to extract oxygen in the form of water**
  - **Capture, quantify, and display the water generated**

RESOLVE Top-Level Science/ISRU Requirements

- **Measure the water and hydrogen bearing volatiles content in a lunar subsurface**
  - **Determine the horizontal and vertical distribution of hydrogen and hydrogen bearing volatiles**
    - Measure the spatial distribution of hydrogen and hydrogen bearing volatiles with a min. horizontal resolution of 2.0 meters and a minimum vertical resolution of 0.25 m.
    - Measure neutron flux consistent with at least 0.5 wt% water equivalent hydrogen,
    - Measure 0.5 wt% water-equivalent layer at 1 meter depth under a dry overburden, with 25 cm depth resolution
    - Measure spatial OH and H_2O in the Near IR spectrum
  - **Extract subsurface material**
    - Extract a subsurface sample up to a depth of 0.75 m. (Goal of 1 m)
    - Maintain a minimum of 1 subsurface core segment per core below 175 deg K (-98 deg C)
    - Selectively accept sections of an acquired subsurface sample
    - Obtain augured cuttings from a depth of 0.5 meters
  - **Measure the abundance of water and hydrogen bearing volatiles in the lunar subsurface**
    - Quantify water in the lunar regolith when water concentrations are between 0.5% to 8.0% (95% TBR) by mass
    - Process a minimum of 40 subsurface core segments.
    - Heat lunar regolith samples to a minimum of 425 deg K (150 deg C) for volatile extraction.
    - Identify and measure the relative abundance of the volatile constituents of the lunar regolith below 70 amu
    - Measure the isotope ratio of Deuterium/Hydrogen and Oxygen 16/18
- **Measure geotechnical characteristics of the lunar highlands and cold traps**
  - Measure the distribution of grains in the lunar regolith with respect to size and shape. (GOAL)
  - Measure bulk characteristics of lunar regolith
  - Determining geotechnical parameters of the drilling media during the sample acquisition phase
  - Identifying mineralogical features in the lunar regolith
- **Demonstrate oxygen extraction from regolith using the Hydrogen Reduction process**
  - Heat samples to 1175 K (902 C) to hydrogen reduction
  - Measure water vapor produced
  - Image water condensate/droplets produced during volatile analysis and H_2 reduction

RESOLVE Development Toward Flight

Internal Call for Proposal Awarded 2006 — **Performed Lunar Polar Design Ref Mission**

Lab. Tests — **1st & 2nd ISRU Analog Test** — **3rd ISRU Analog Test** — **Lunar Env. Chamber Test**

Gen I
2006-2007
Demonstrate Feasibility & Subsystem Performance
- **Hardware designed to demonstrate functions needed for RESOLVE**
- Minimal integration between functions
- Minimal software and autonomous control development
- No mission operation considerations
- Not considered in design:
  - Flight environment
  - Mass, power, and volume
  - Mission operations

Gen II
2007-2008
Demonstrate Integration & Operations
- **Hardware designed to demonstrate functions needed for RESOLVE in one 'flight like' package**
- Flight mass and volume for RESOLVE functions considered in design
- Start of software and control development
- Start of mission operation considerations
- Not considered in design:
  - Flight environment
  - Flight-like avionics and power conditioning, and ground support hardware

Gen IIIA
2010-2012
Develop 'flight like' unit for mission simulation
- **Hardware designed to address lunar polar ice/volatile mission requirements**
- Software and control development
- Focus on mission operations
- Design to operate under lab/analog conditions with path to lunar env.

Gen IIIB
2012-2014
Develop flight prototype for vacuum operation
- **Hardware designed to operate under lunar conditions**
- Focus on
  - Flight design for all RESOLVE hardware
  - Software & control of hardware operation
  - Mission operation timeline and power profile
  - Environment: vacuum, temperatures, EMI, materials

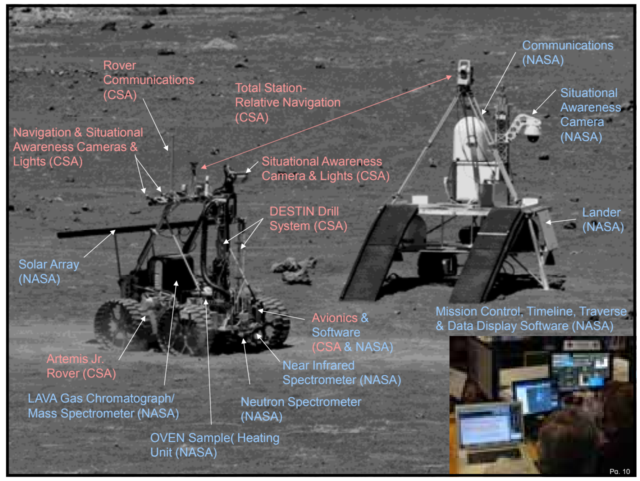
Test Site on Hawaii Very Much Like the Moon!

RESOLVE Analog Field Tests

Nov. 2008
- **RESOLVE Gen II on Scarab Rover**
- Power, avionics, and ground support equipment on separate trailer

FEB. 2010
- **RESOLVE Gen II+ on CSA Juno Rover**
- Power, avionics, and ground support equipment on separate Juno

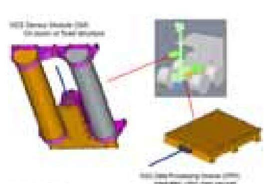
July 2012
- **RESOLVE Gen IIIA on CSA Artemis Jr. Rover**
- Everything on single rover platform



Neutron Spectrometer Subsystem (NSS) Functions & Design Constraints

NSS Functions
- Determine the horizontal and vertical distribution of hydrogen and hydrogen bearing compounds/minerals
  - Map to 1 meter depth and ~ 1 m wide path
  - Map to depth at rover speed ≤10 +/- 1 cm/s
- Detect water at a minimum abundance of 0.5% by mass with <10% uncertainty
- Operate ≥ 6 hrs in permanently shadowed area

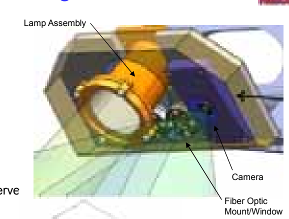
NSS Design Constraints
- Mount ~1 m above the surface aimed in front of the rover
- Operate -30 to +40 °C
- Max temperature change rate: 20 °C /hour
- Instrument Mass: 1.85 kg
- Power: 2 W ave.; <4 W max for heaters



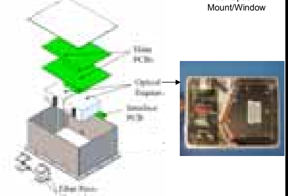
NSS Brassboard

Near Infrared Volatile Spectrometer Subsystem (NIRVSS) Functions & Design Constraints

NIRVSS Functions
- Quantify amount of water in lunar regolith at a minimum abundance of 0.5% by mass
- Identify surface bound H_2O/OH
  - Map at rover speed ≤10 +/- 1 cm/s
- Bound understanding of mineral content in regolith
- Identify volatiles, including water content and form evolved during auger/drilling
- Bound volatile presence in top 20-30 cm of regolith during auger/drilling
- Enable observation under all lighting conditions
- Image drill area with sufficient Field Of View to observe 22 cm of tailings with resolution at ~200 μm scale
- Operate ≥ 6 hrs in permanently shadowed area



NIRVSS Design Constraints
- Identifying volatile and mineralogical features in the near-infrared spectrum in the range of 1.8-3.2 microns with a spectral resolution of less than 0.05 μm.
- Mount Near IR, Camera, and lamp to view auger/drill area
- Achieve SNR ≥100 at 3 μm while drilling
- Operate +0 to +45 °C
- Mass: 7.7 kg
- Power: 16.31 W ave (NIR, camera, & lamp)

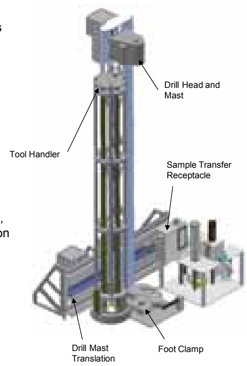


Spectrometer Assembly

Sample Acquisition Subsystem: DESTIN Functions & Design Constraints

DESTIN Functions
- Penetrate substrate 1m to collect, retrieve, transfer samples from >0.75 m
  - Unconsolidated regolith to consolidated
- Auger material to surface from depth up to 0.5 m
- Maintain sample phase, chemical state, and stratigraphy
- Sample Transfer Receptacle (STR)
  - Section samples to 12.5 cm length x 1.6 cm dia.
  - Deliver ≥90% of sample to OVEN
  - Deliver sample to OVEN at <150 K
- Minimize sample cross-contamination
- Abandon drill rod if stuck and recover
- Autonomous operation in shadowed region for ≥6 hrs
- Measure temperature near core
- Measure: sample hardness, energy required for penetration, rate of cut, drill depth, instantaneous drilling power, weight on bit, torque, rpm

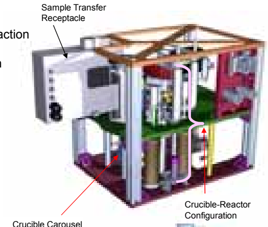
DESTIN Design Constraints
- Dimensions of all components <1.35m x 0.75m x 1m
- Safe position must not interfere with rover locomotion
- Operate when titled up to 15 degrees
- No consumables
- 50 auger/drill operations
- Mass: <40 kg max.; 25 kg goal
- Power: <150 W ave.
- Static Force: 120 N max.

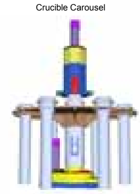


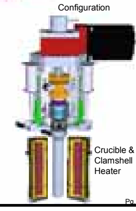
Oxygen and Volatile Extraction Node (OVEN) Functions & Design Constraints

OVEN Functions
- Heat multiple samples to 423 K (150 °C) for volatile extraction
- Heat a minimum of one sample to 1173 K (900 °C) in presence of hydrogen for oxygen extraction from regolith
- Accept sample from Sample Transfer Receptacle (STR)
  - May be solid core or granular material: 16 mm dia. by 125 mm ; 25 to 60 gms
- Accept samples at <150 K
- Maintain samples at <175 K prior to sealing.
- Measure sample mass before and after processing to +/- 0.1 gm accuracy
- Dump sample after processing to remove a minimum of 95% of sample material
- Selectively accept and reject (dump) sample without processing
- Transfer volatiles released (at 150 and 900 °C sample temperatures) to surge tank in analysis and water droplet demo.

OVEN Design Constraints
- Minimum leak rate during sample processing - psi over 4 hrs at 100 psi (at 150 and 900 °C)
- Heat 40 samples in 5-7 day mission
- Mass: 10 kg
- Power: <300 W ave.
- Minimize height of OVEN subsystem since STR drill tube must extend above OVEN







Lunar Advanced Volatile Analysis (LAVA) Functions & Design Constraints

LAVA Functions
- Accept gas samples from OVEN at up to 100 psi and 423 K (150 °C) to 1173 K (900 °C)
- Identifying and measuring the relative abundance of the volatile constituents of the lunar regolith.
  - Quantify amount of evolved water ~~in~~ from the lunar regolith at a vapor concentration of 0.1% to 95% with a standard deviation of 5% relative standard deviation or the absolute standard deviation of 0.2% water , whichever is greater
  - Measure volatile constituents of the lunar regolith to 70 amu including, CO, H_2O (g), H_2, [H_2S, NH_3, SO_2, C_2H_4. are Goals]
  - Measure the D/H and $O^{16/18}$ isotope ratios (Goal)
- Collect and provide images of water collected through volatile extraction and hydrogen reduction of regolith
- Provide and regulate hydrogen gas to OVEN for Regolith Oxygen Extraction

LAVA Design Constraints
- Complete GC-MS analysis in under 2 minutes
- Mass: 15 kg
- Power: <100 W ave.

Surge Tank and Fluid Subsystem


Water Droplet Demo w/ Camera


Gas Chromatograph/Mass Spectrometer

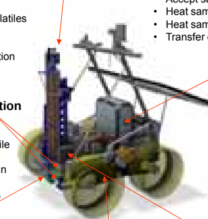
RESOLVE Gen III

Purpose: Develop a flight-like unit that can fit on a rover and operate in the lunar environment

Sample Acquisition System
Auger/Core Drill Subsystem [CSA]
- Collect and transfer subsurface material down to 1 m below surface
- Maintain sample stratigraphy and volatiles (below 150 K)
- Meter samples for processing
- Auger material to surface for evaluation
- Measure geotechnical properties of regolith during drilling

Surface Mineral/Volatile Evaluation
Near Infrared Volatile Spectrometer Subsystem (NIRVSS) - ARC
- Measure surface bound OH/H_2O while traversing (at min. of 0.5% by mass)
- Detect form of water (ice/hydration) in auger tailings
- Detect water vapor in evolved gases
- Image surface and drill tailings

Resource Localization
Neutron Spectrometer Subsystem (NSS) -ARC
- Locate hydrogen and hydrogen bearing volatiles down to 1 meter below the surface while traversing (at min. of 0.5% by mass)



Volatile Content/Oxygen Extraction
Oxygen & Volatile Extraction Node (OVEN) - JSC
- Accept samples from Sample Acquisition System
- Heat samples from <150 K to 423K for volatile extraction
- Heat samples to 1173 K for oxygen extraction
- Transfer evolved gases to LAVA volatile analyzer

Volatile Content Evaluation
Lunar Advanced Volatile Analysis (LAVA) - KSC
- Accept evolved gas from OVEN; provide hydrogen for oxygen extraction
- Perform analysis in under 2 minutes
- Measure water content in evolved gas
- Characterize volatiles of interest (below 70 amu)
- Measure D/H and $O^{16/18}$ isotopes
- Capture & image water evolved

Operation Control Flight Avionics - KSC
- Space-rated microprocessor
- Control subsystems and manage data

Surface Mobility [CSA]
- Traverse wide range of lunar surface/material conditions
- Tele-operation and autonomous traverse modes
- Carry RESOLVE payload; provide power, comm., and thermal management

RESOLVE Mission Requirements
- Nom. Mission Life = 5+ Cores; 14 Days
- Mass = 170 kg rover/80 kg payload
- Ave. Power; 200-300 W

Vacuum Demonstration Unit GCMS Design: Integrated COTS Approach

Changes required for Vacuum Unit –Flight forward

-

Maintain fast scan rate and analyte sensitivity
-Less mass
-Less power
-More rugged (Vibe tolerant)
-Dilution capability (prior unit saturated at about 5% water)
-Software control from Xiphos- Payload control
-Integrated Avionics controlled by payload
-Thermal Vacuum (materials and electronics)

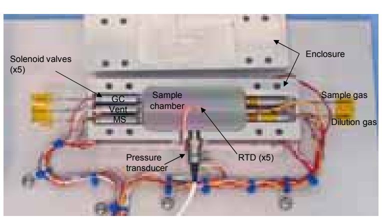
Vacuum Chamber – Bell Jar

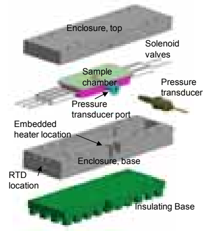
Inner Diameter - 13”
Total Height - 27”
Varian Turbo-V80 Turbo Vacuum Pump

Current configuration:
7 Total Ports – 5 Available for feed-throughs
- Pressure Transducer & Ion Gauge
- 20-pin Electrical Port
- Double ¼” Swagelok Port
- Single 1/8” Swagelok Port

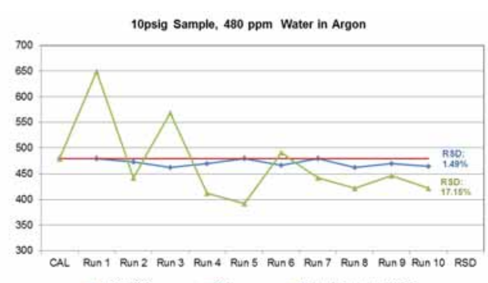
RESOLVE Sample Delivery System (SDS)

- Temperature and pressure-controlled sample chamber that provides a consistent sample environment for the GC or MS
- Accurately manages temperature (0-150°C) and sample pressure (0-35 psia), with the goal of reducing sample carry over, particularly water
- Can control sample gas and dilution gas delivery to target desired concentration ranges





SDS Performance



- SDS conditioning proved to be key for stable water quantification using GC
- High temperature conditioning sample with SDS (e.g. 140°C) provided much better water signal stability and repeatability

Key Performance Parameters (KPP)

Performance Parameter	State of the Art	Threshold Values	R&TD Goals	Actual Values / Current Best Estimate
System Mass	15 kg	15 kg	11 kg	14.94 kg ETU (14.69 kg for flight) (MEL input, 5/1/13)
Average Power[1]	80 W	100 W	80 W	75 W checkout (PEL, 2/28/13)
Peak Power	163 W	200 W	160 W	200 W (PEL, 2/28/13)
Water Vapor Concentration[2]	N/A[3]	0.5-95%	0.1-99%	0.1–99% (Test Data 6/3/2013)
Mass range (MS systems)	Ion trap 12-150amu Mag Sector 2-130amu Quad 1-60amu (1.8sec/mass scan) All Scanning	Demonstrated data collection of a full mass spectrum at a sample rate of ≥ 6 Hz for 1-65 AMU	Demonstrated data collection of a full mass spectrum at a sample rate of ≥ 6 Hz for 1-80 AMU	6.7 Hz, 1-70 AMU (Test data, 5/3/13)

[1] State of the art values are based on laboratory instruments, not flight instruments
[2] Gas phase concentration, does not refer to percent mass in soil
[3] Not stated for existing flight instruments, depends on background levels and carry over

GC Evolution (Inficon)

COTS (1st Gen)	2nd Iteration
Cold spots (TCD and other Connectors)	Thermal control of heated zones
Operated by COTS software	Operated by Q6
Column oven inefficient and heavy	Decreased mass and power usage
Portable design	More rugged design

First Generation GC Second Generation GC

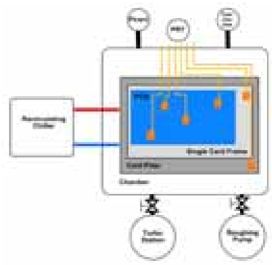
MS Evolution (OIA)

COTS	1st Iteration	2nd Iteration
Integrated vacuum chamber	No vacuum chamber	No vacuum chamber
1.1 Kg magnet	1.1 Kg magnet	0.6 Kg magnet
Two detector boards	Two detector boards	Merged detector boards
Mounted to wall of vacuum chamber (3.9 Kg)	Mounted to lighter material base (2.0 Kg)	Mass further reduced (1.5 Kg)
No dust shield	Full/partial dust shield	Full dust shield
No internal thermal isolation	Internal thermal isolation	Internal thermal isolation
Standard electronics	Standard electronics	Some modified electronics
Electronics in ambient air	Electronics in ambient air	Electronics in vacuum

MS Design Iteration 1

- COTS Instrument
  - HV tester (hardware)
  - IonCam w/ Silconert
- Fabrication
  - Bell Jar MS
- Software
  - Three ICDs
- Design Trades (to be detailed later)

MS Thermal and Thermal Vacuum Testing, IHV



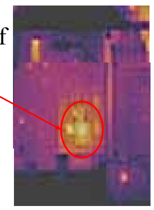
Future testing for other COTS boards will utilize PRTs in this manner.

IonCam operating with the IHV board in thermal vacuum.

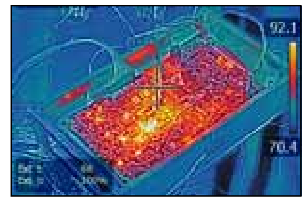
Thermal Imaging

- Thermal imaging was used on the board operating in ambient air to determine location of heat sources.

Majority of heat from Blackfin processor



DIG Board



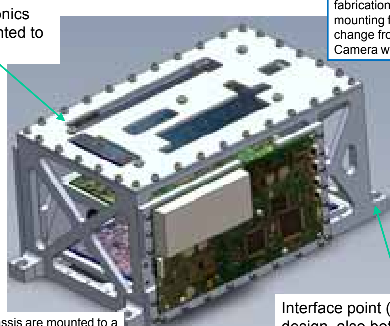
IHV Board in Mounting

Cover was removed and temperatures were at steady-state: thermocouples were not attached. Camera setting was auto range. Vacuum-side was on.

MS Electrical: Thermal Management

Current status: Card chassis are in fabrication. Final design of mounting frame in progress (may change from what is shown). IR Camera work in progress.

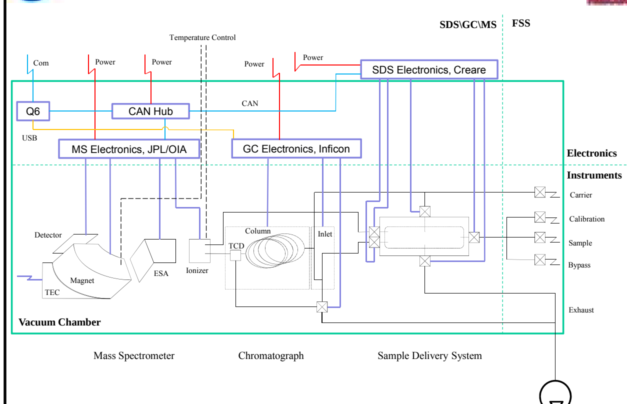
Each electronics card is mounted to a chassis



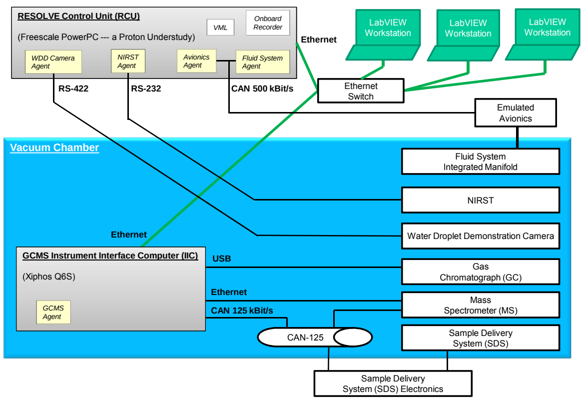
The various chassis are mounted to a frame which sinks heat into an interface with RESOLVE.

Interface point (4 in current design, also bottom surface of frame).

SDS/GC/MS Block Diagram



LAVA Software Overview – ETU Architecture



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Vacuum Demonstration Unit GCMS Design: Integrated COTS Approach

RESOLVE AES/OCT Project Status

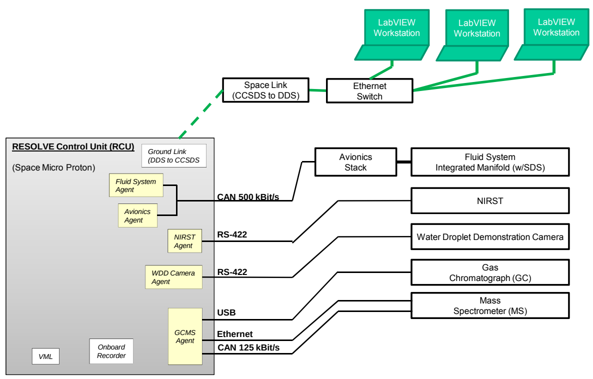
Gen IIIA: Field Development Unit (FDU)

FDU System Requirements Review	03/03/11	*Completed*
FDU 30% Design Review	05/25/11	*Completed*
FDU 90% Design Review	08/26/11	*Completed*
FDU 90% Delta Design Review	10/28/11	*Completed*
Field Demo Subsystem HW Initial Delivery to KSC	02/27/12	*Completed*
Field Demo HW Integration onto Rover Complete	06/29/12	*Completed*
Field Demo HW Delivered to Field Test Location	07/09/12	*Completed*
Demonstrate Integrated RESOLVE ops on Rover in Field Test	07/27/12	*Completed*
AES Project Continuation Review	09/18/12	*Completed*

Gen IIIB: Engineering Test Unit (ETU)

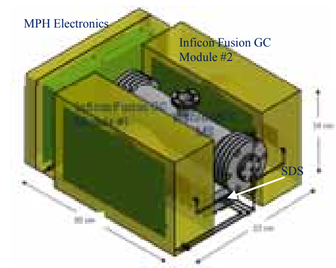
ETU SRD Initial Delivery	12/16/11	*Completed*
Complete ETU System Requirements Review	08/29/12	*Completed*
ETU 30% Design Review	12/14/12	*Completed*
ETU 90% Design Review	07/26/13	*Completed*
AES Project Continuation Review	09/13	
OCT Project Evaluation/Continuation Review	09/13	
ETU Subsystem Environment Testing Complete	05/12/14	

LAVA Software Overview – Flight Architecture



Brassboard GC/MS for RESOLVE

Ken Wright (Inficon); Andres Diaz (NTCR); Bob Kline-Schoder, Paul Sorensen, Brandon Smith (Creare)



INFICON's Transpector MPH:

- Ultra Fast Measurements (0-65 m/z @ 8.5Hz).
- High Sensitivity and Low Noise = Lower Minimum Detectable Partial Pressure (<1E-15 torr).
- Smaller and Lighter (>30% weight reduction)
- Nine Decades of Dynamic Range.
- New High Performance and Field Replaceable EM/FC Detector (Developed with Detector Technology Inc.).
- Field Replaceable Dual Filament Assemblies (W or Y2O3/Ir).
- Easy to Use Programming Interface - JSON over HTTP or LabVIEW.

Continuing Challenges

Budgetary Cuts

Requirements evolving

Commercial Partners Deliveries/IP issues

Flight Forward Plans

- Stand down on purchases until payload matures
- Ground Calibration
- Failure Mode Testing
- Material off-gassing testing
- Vibe tests
- Verification and Validation
- Compare results from SBIR Phase II