Printable Spacecraft

Flexible Electronic Platforms for NASA Missions

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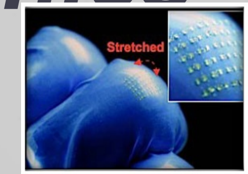
Flexible Printed Electronics

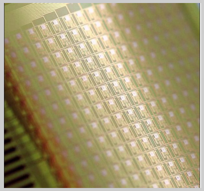
Substrates

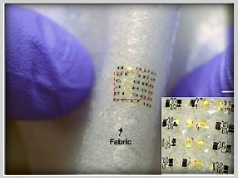
Flexible, stretchable, dissolvable

Polyimide	Silicon	Kapton
Metallic sheet	Polymers	Ceramics
Plastics	Glass	Paper

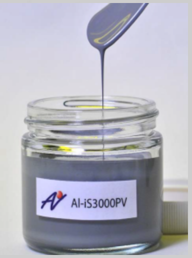


mc10
High Performance Conformal Electronics





DUPONT
The miracles of science



Applied Nanotech, Inc.

Inks

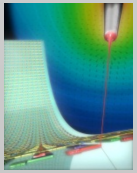
Aqueous, catalyst, CNT infused, etched

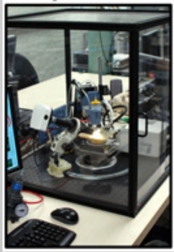
Photovoltaics	Conductors	Metals
Polymers	Insulators	Semiconductors

Manufacturing

High precision, sheet based, production

Plasma Flame	Roll to Roll	Gravure
Aerosol-jet	Ink-jet	Flexo
Screen printing	Transfer	E-jet



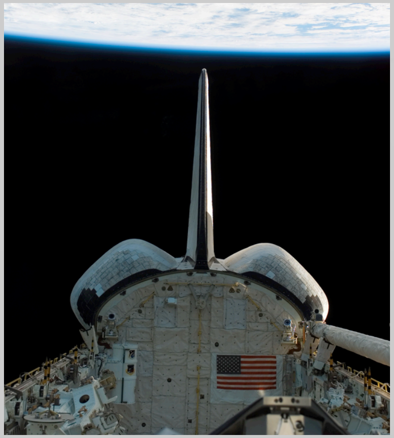


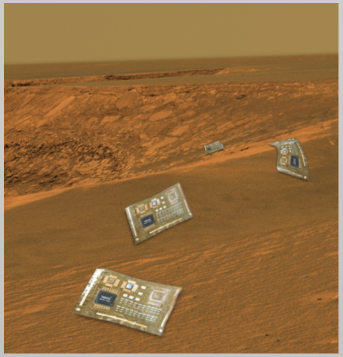
PolyIC
The chip printers
a member of the KURZ Group

What is a Printable Spacecraft?

Imagine….editing your spacecraft on a laptop, printing it using an inkjet printer and deploying thousands of copies…..

- A two dimensional "sheet" that contains all of the functional subsystems of a typical spacecraft - science measurement through data downlink.
- Functional circuits would be designed compatible with flexible electronics "printing" techniques.
- All elements are printed onto a common substrate.





Advantages and Challenges

- Benefits of Flexible Printed Electronics
  - Flexible platform allows storage and deployment options, changing shape on orbit, or conform to surfaces
  - Low recurring costs enables large numbers or “disposable” for hi-risk environments
  - Low mass & volume enables large numbers or secondary payloads
  - Short cycle time allows Iterative testing and evaluation
- Challenges
  - Advances in component performance
    (e.g. circuit speed, memory, RF frequency).
  - Sensor systems for complex science
  - Environmental compatibility
  - Integrated system design
  - Manufacturing compatibility
  - Mission applications and benefits

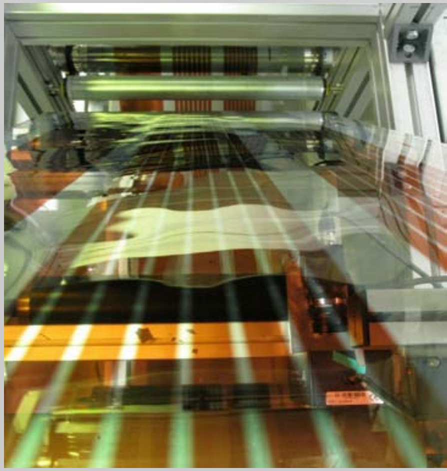


Image Credit: VTT

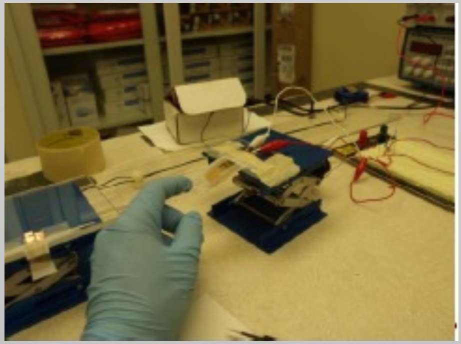
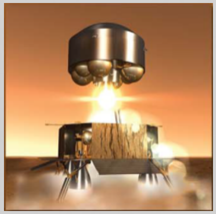


Image Credit: US Army

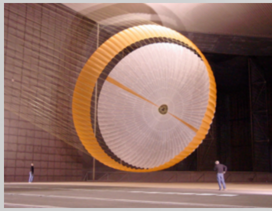
NASA Applications for PE

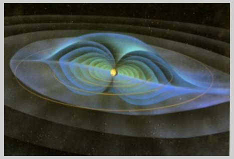



Engineering

Reconfigurable, Conformal Sensing, Intelligent Structures

Origami Structure	Soft Goods	Hull Integrity
Mobility	Wheel/Soil interaction	Medical Patch
Cubesats	Sample Canister	Tank Volume

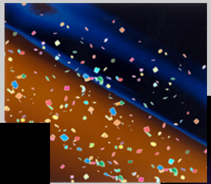
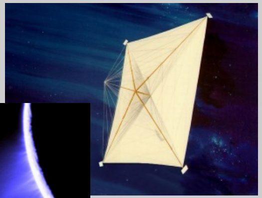
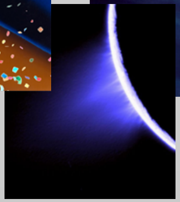



Potential Mission Enhancing

Networks, Space Physics, Sounders, Probes

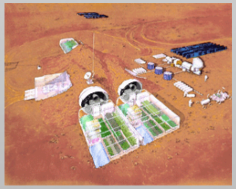
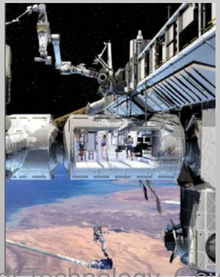
Comet Sample Return	Venus Climate Mission
Mars Environment Network	Saturn Probes


Enabling Potential New Concepts

Exploratory, High Risk, Swarms

Atmospheric Confetti	Enceladus Volcanic Probe
Interstellar Sail	Inchworm crawlers

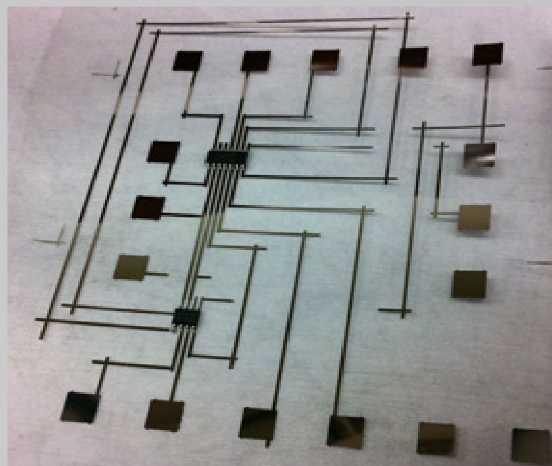
In-Situ Manufacturing

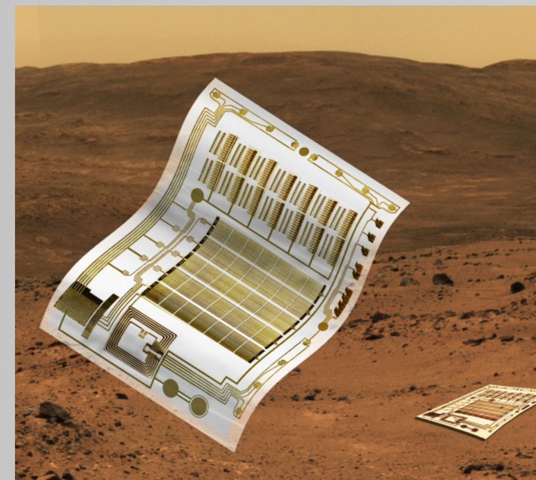
Responsive, Efficient, Directed

Space Station	Human Outposts	Robotic Stations

NIAC Printable Spacecraft Task Elements

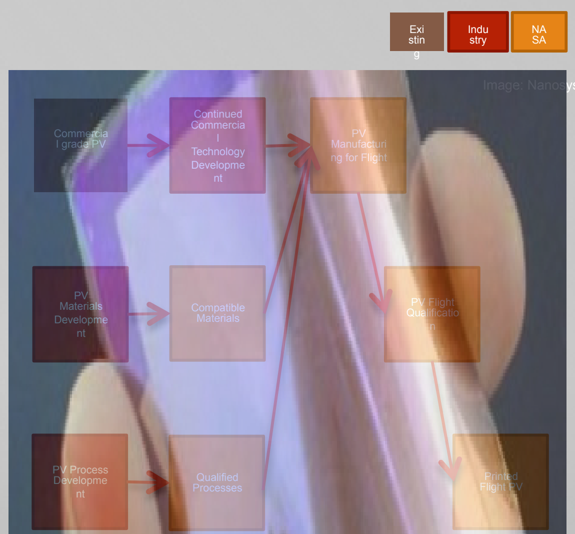
Design, build and demonstrate an end to end spacecraft platform

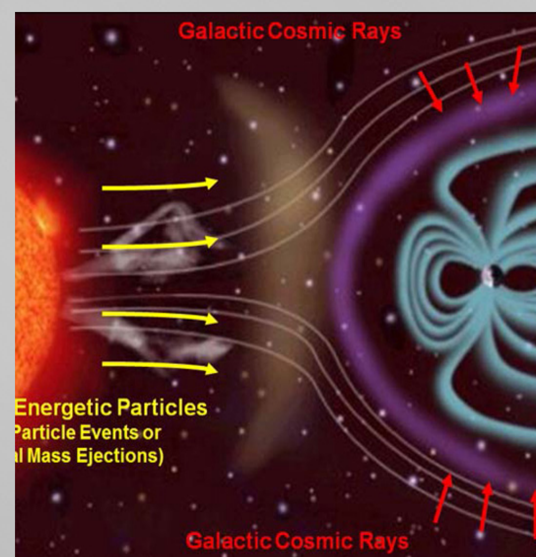




Define a scientific reference mission to evaluate the programmatic benefits of infusing printed spacecraft.

Develop roadmaps for multiple applications and focused mission infusion.





Test printed electronics coupons in space environments and evaluate compatibility

Printable Spacecraft Phase 2 Tasks

Reference Mission

Define a Mars surface environmental network as a “reference mission” to guide other phase 2 tasks.

FY 13				FY 14			
Q1	**Q2**	Q3	Q4	Q1	Q2	**Q3**	Q4

Team X Study

Perform a Team X study to ascertain cost, schedule, programmatic benefits of the printable spacecraft vs traditional approach – in the context of the reference mission.

FY 13				FY 14			
Q1	Q2	Q3	Q4	**Q1**	**Q2**	Q3	Q4

Prototype Platform

Design and fabricate an integrated system from sensors to communications.

FY 13				FY 14			
Q1	Q2	**Q3**	**Q4**	**Q1**	**Q2**	Q3	Q4

Environmental Testing

Test functional component samples in environments defined by reference mission (vacuum, temperature range and cycling, radiation).

FY 13				FY 14			
Q1	Q2	Q3	Q4	**Q1**	**Q2**	Q3	Q4

Roadmaps

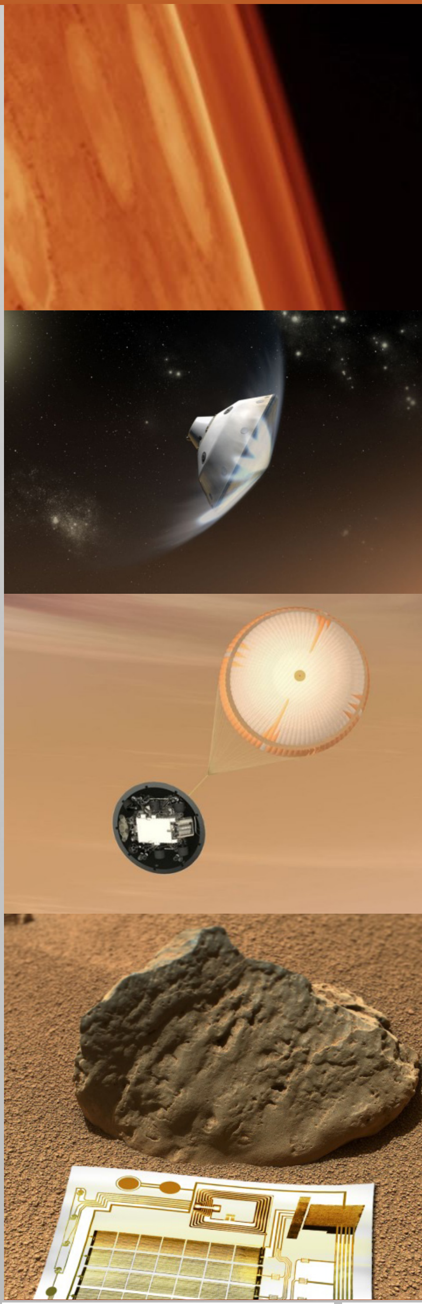
Define a roadmap for the reference mission and develop more detailed roadmaps for PE technology development and early demonstration milestones.

FY 13				FY 14			
Q1	Q2	Q3	Q4	Q1	**Q2**	**Q3**	Q4

Reference Mission: StANLE

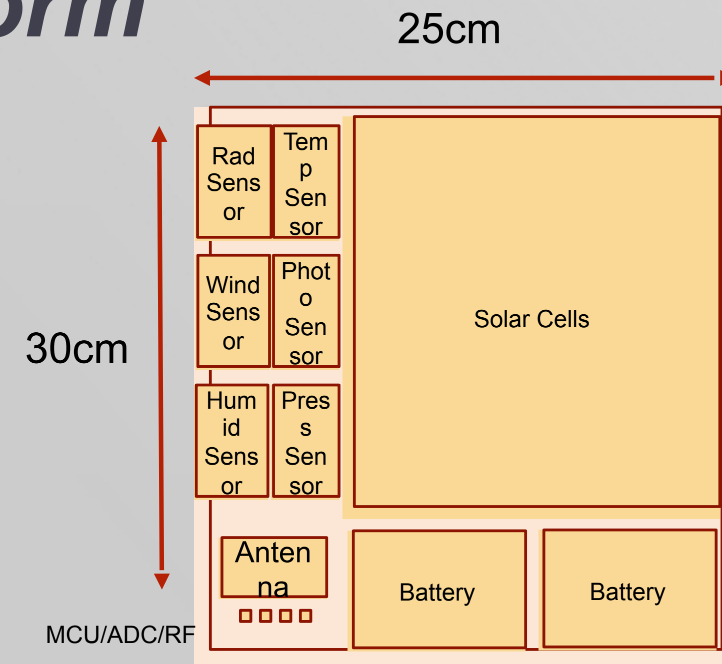
….**St**ructure of the **A**tmosphere: **N**etwork **L**ander **E**xperiment

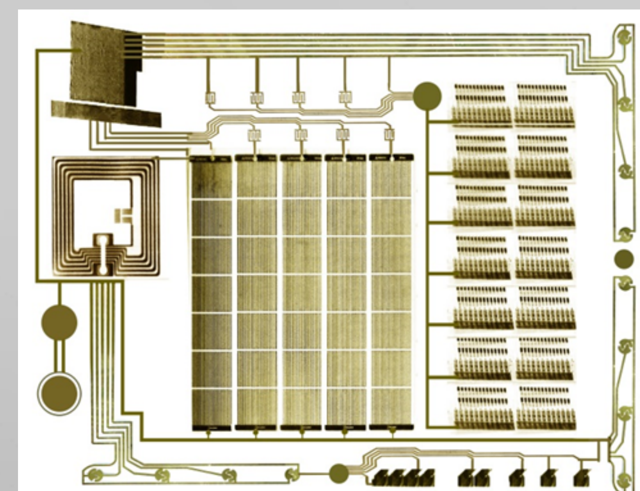
- A Mars environmental network mission to study the structure of the atmosphere through measurements at tens of thousands of locations across the surface.
  - We examined previous network mission concepts to extract relevant science and measurements objectives.
- Temperature, Pressure, Wind Speed, Atmospheric Opacity, Radiation, and Humidity measured once every hour for a Martian year.
- A traditional Mars entry system is used which, after heatshield separation, releases the printed electronic platforms into the atmosphere, allowing them to flutter to the surface and begin their mission.
  - Defined project and mission parameters
  - Sized a platform for anticipated functionality
  - Studied aerodynamic effects for distribution and stability



Reference Mission: Platform

- The StANLE lander is approximately 25x30 cm containing the functional elements of the science platform.
  - Total system mass <4.5 grams
- The instruments sample at a rate of one sample per hour continuously.
- The platform produces 1 W of total power to operate the sensors and data circuits and support communications to an orbital asset via a UHF relay link at least once per day.
  - The battery provides enough energy to continue the platform operations through the night.
- All subsystems have been sized based on realistic projection of technology advancements
  - Hybrid approach to data system and RF electronics

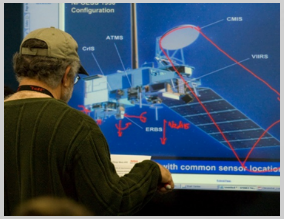


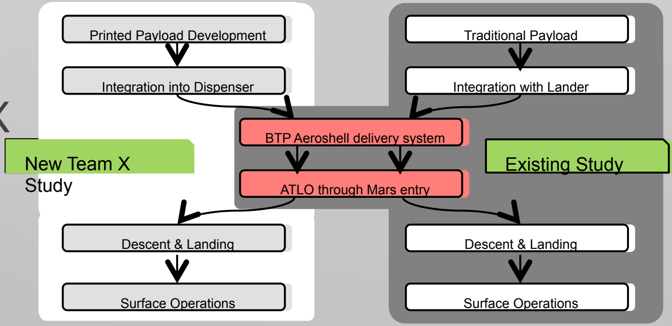


Team X Study

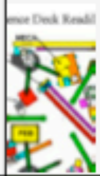
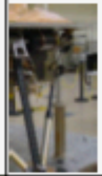
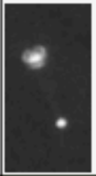
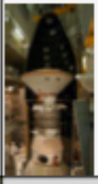
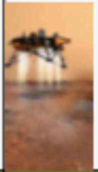
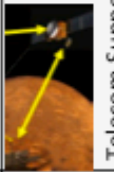
The Team X study will evaluate the programmatic advantages of a network mission based on a printed lander compared to traditional lander.

- Accomplishments
  - Reviewed previous relevant Team X studies to help establish a baseline .
    - Start with an existing design/study for a single lander , rework it for the 2024 opportunity.
    - Delta off that study for the expected changes due to Printed Lander
  - Defined subsystem evaluations and relevant products of the study.
  - Defined a “scorecard” of schedule, risk, cost
- Work to Go
  - Refine study ground rules and input material for Team X
  - Prepare kickoff briefing charts
  - Execute session
  - Extract conclusions and recommendations





Scorecard Hypothesis: Printed vs Traditional

	 Payload Hardware Development	 CS /EV Hardware Development	 Descent and Landing HW Dev.	 System I&T	 Launch Operations	 Cruise Operations	 Entry Phase thru HS separation	 Descent and Release	 Landing	 Surface Operations	 Telecom Support Assets
Mass	P	S	P	NA	S	NA	S	P	P	NA	NA
Cost	P	S	P	P	S	S	S	P	P	P	?
Schedule	P	S	P	P	S	S	NA	NA	NA	S	NA
Risk	T	S	P	T	S	S	S	P	P	T	T

Printed

Traditional

Same

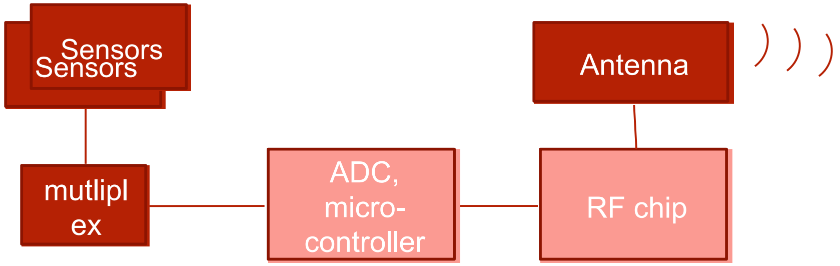
Team X Study will validate and quantify the "scorecard"

NIAC Printed Spacecraft Project

Project Objective

Develop a highly functional, lightweight, mechanically flexible printed prototype demonstration unit that measures 2 different environmental stimuli and wirelessly transmits the data

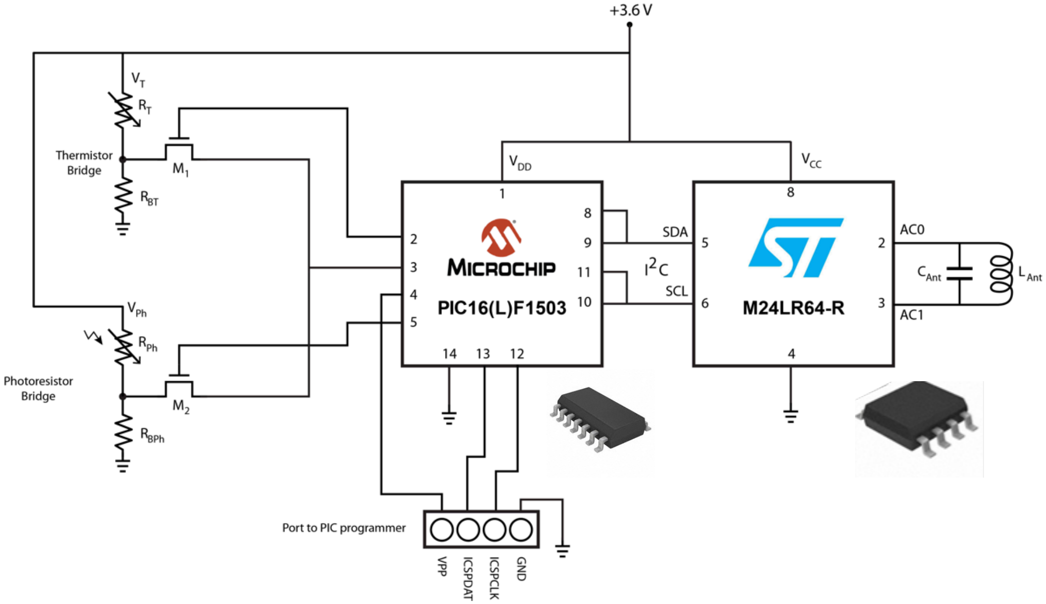
- Use a combination of microelectronic and printed components
- Power provided from external source.



Advances in State of the Art include

- Demonstration of intersystem functional compatibility of various printed devices and micro-electronics
- Demonstration of Low Voltage TFTs
- Demonstration of multiplexing continuous data from multiple sensors.
- Demonstration of new sensor design.

System Design



<u>Printed components</u>:

- Thermistor R_T & Photoresistor R_{PH}
- Resistors R_{BT}, R_{BPh}
- Antenna L_{Ant}
- Capacitor C_{Ant}
- TFTs M1, M2
- All interconnects

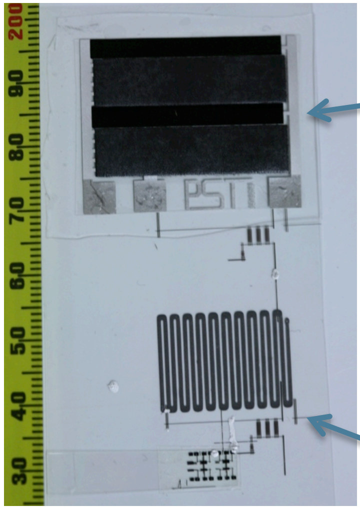
<u>Discrete components</u>:

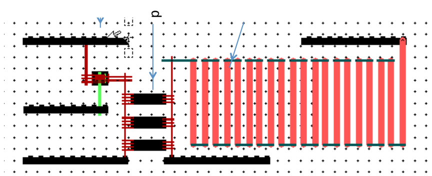
- PIC: 8 bit, 16 MHz, 10 bit ADC
- RF Chip: 13.56 MHz NFC I/O, ASK modulation, 64 kbit EEPROM

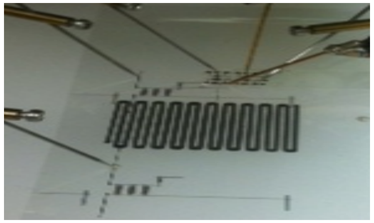
<u>Functionality overview</u>:

- System operating voltage 3.6V
- Divider R_T / R_{BT} outputs temperature-dependent voltage
- Divider R_{Ph} / R_{BPh} outputs light (or opacity)-dependent voltage
- TFTs M1 and M2 multiplex sensor outputs
- PIC built-in ADC converts sensor outputs to digital values
- Sensor output plus timestamp sent over I2C to RF chip, and stored in EEPROM
- Signals sent over NFC from RF chip to reader

Sensors

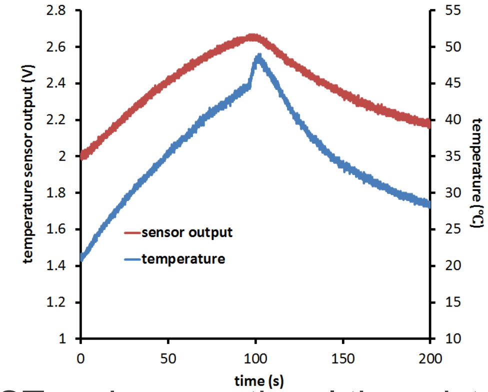






Thermistor

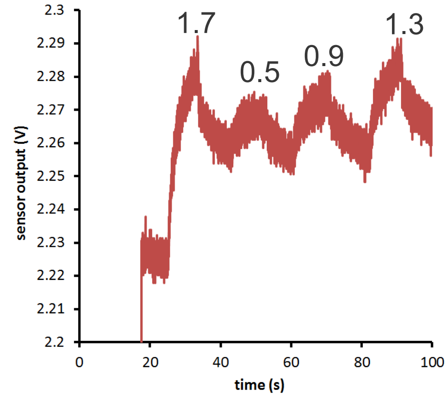
- Fabricated by PST
- Silicon nanoparticles
- Silver contacts
- Carbon resistors
- Screen printed
- PET substrate



PST and conventional thermistors tested on hot plate

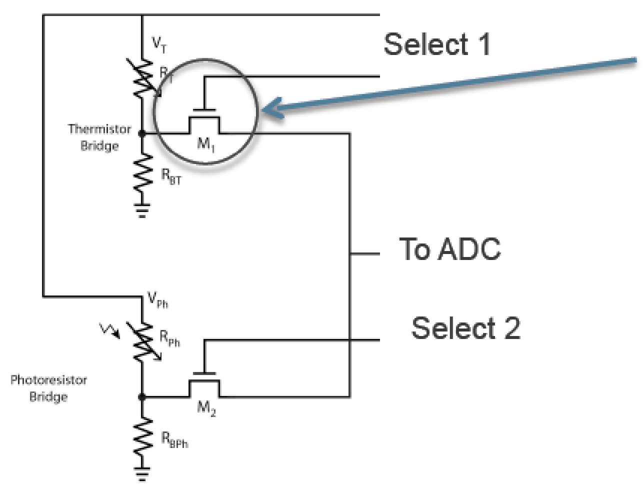
Light Sensor

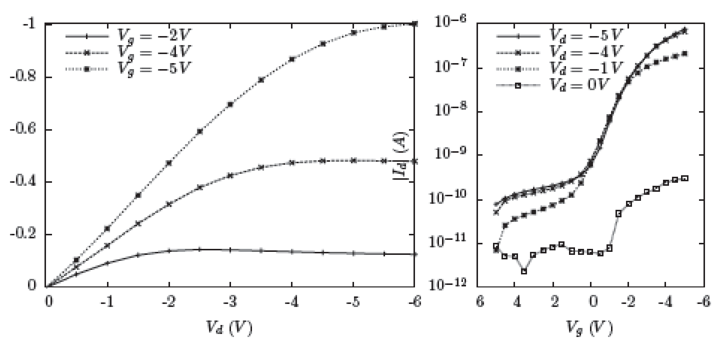
- Developed by PARC
- Printed silver electrodes
- Printed organic semiconductor
- Carbon ink resistors
- PEN substrate



Exposed to 4 levels of intensity in sequence -> 1.7, 0.5, 0.9, 1.3 mW/cm^2

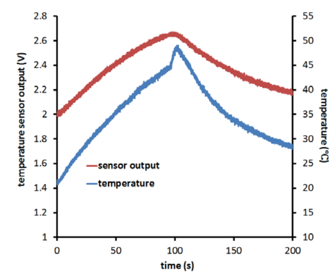
Multiplexing Circuit

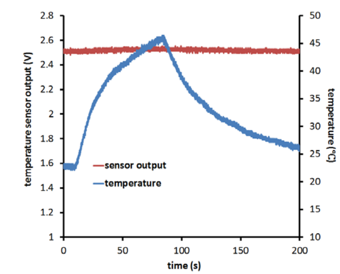




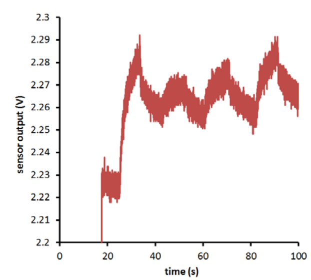
Low Voltage TFTs

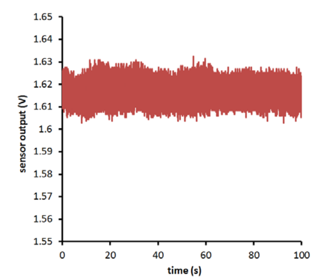
- Inkjet printed p-type organic TFTs with high-k polymer dielectric
- Lower voltage operation than typical printed TFTs (usually 10s of volts)
- Can operate at 3.6 V, enables integration of printed and microelectronic components without the need for further circuitry





Thermistor



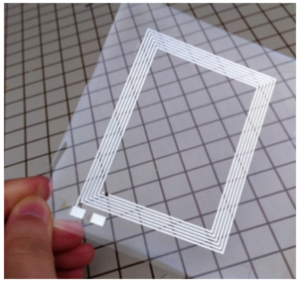


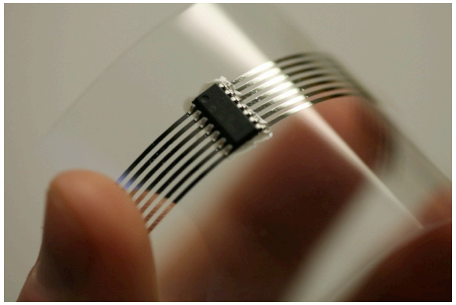
Photosensor

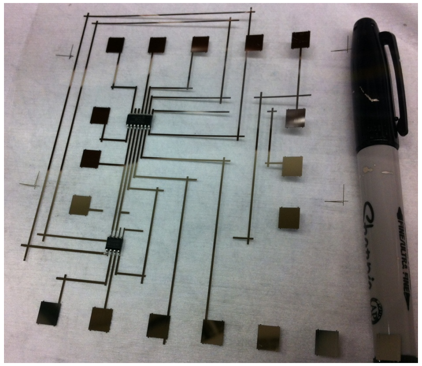
Gate ON Gate OFF

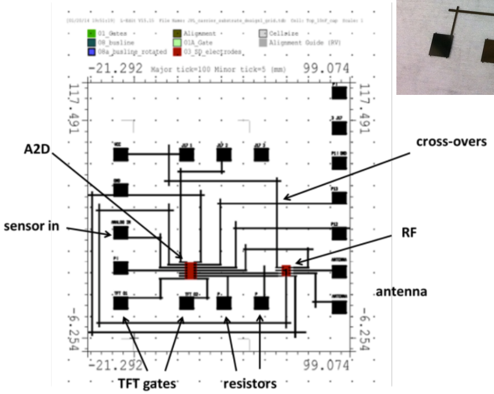
Engineering Functions & Interconnects

- Chip attachment to printed interconnects and flexible substrate demonstrated
  - PEN substrate
  - Anisotropic conductive adhesive
    - Lateral resistivity ~ $10^9\ \Omega$ m
    - Vertical resistivity ~ $10^{-6}\ \Omega$ m
  - Thermoplastic or thermoset
  - Screen/extrusion printable
- Antenna printed and tested
  - Silver paste applied through digital extrusion printing
- Full end to end circuit PCB breadboard functionally tested with printed peripherals.
  - Data generated by sensors and transmitted to NFC receiver using PCB.
- Master substrate design created based on results from PCB, separate elements will be printed, tested, and integrated on this substrate for the final demonstrator









Important Findings

- Low profile, microelectronic chips can allow for highly functional flexible electronic systems, with little compromise in form factor.
- We are learning a lot about engineering the interface between microelectronics and printed electronics
  - This is critical for all printed electronics applications and has not yet been sufficiently studied
- Printed electronics that operate at <5 V important for hybrid sensing systems. Allows for compatibility between printed and microelectronic components, simplifying design
- Flexible anisotropic conductive adhesives work well for making physical interconnection to printed wiring
- Fine pitch interconnects can be made using ink-jet printing, compatible with pad pitch on most bare dies
- Matching between the output impedance of printed sensors and electronics important, impacts the choice of chips that can be used.
- Even when using microelectronic components there are still clear uses for printed circuits such as multiplexing for n sensors
- Development of this hybrid platform will facilitate the use of many other sensor types
- High quality electronics allows simpler sensors to be used.

Work to Go

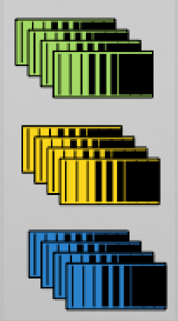
- Optimizing interface between the multiplexing circuits and the PIC A2D.
- Separate elements will be printed, tested, and integrated onto the master substrate for the final demonstrator.
- Performance of final integrated system validated end to end (stimulus to RF data transmission).
- Demonstrator and final report to be delivered to JPL.

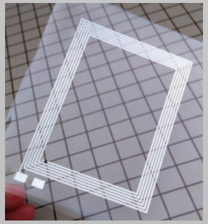
Environmental Test Program

Defined the desired scope, approach and objectives of environmental testing program.

- Accomplishments
  - Completed literature search for published data.
  - Established test objectives for measurements and observables
    - Look for changes in basic physical properties (mechanical and electrical) and robustness to environments.
  - Researched materials properties; down selected to preliminary set
    - Material specimens: substrates (PEN, PEEK, PETE) and inks (Ag ink, carbon ink (CNT), EAPs)
    - Functional samples: Temperature sensors, transistor array, antenna
- Work to Go
  - Peer review on test program and sample selection (Feb)
  - Acquire and manufacture sensors (Feb)
  - Conduct testing (March-April)
  - Document results, findings, and recommendations (April)

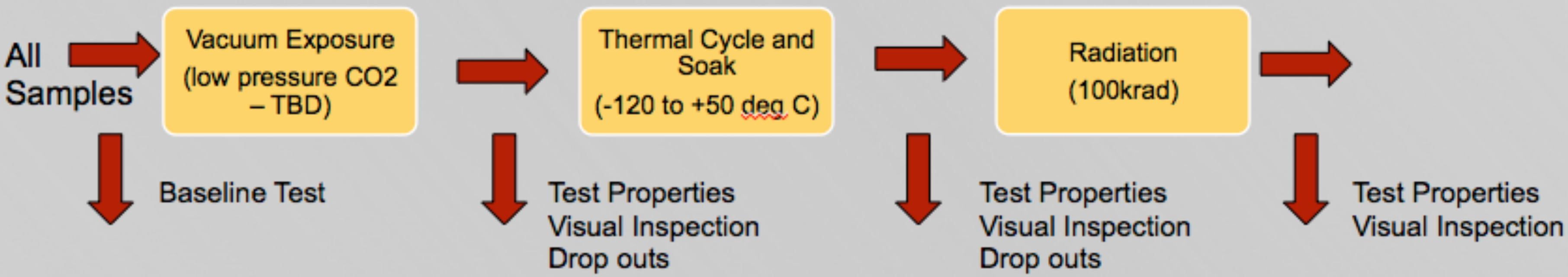
BOEING
Engineering, Operations & Technology
Boeing Research and Technology



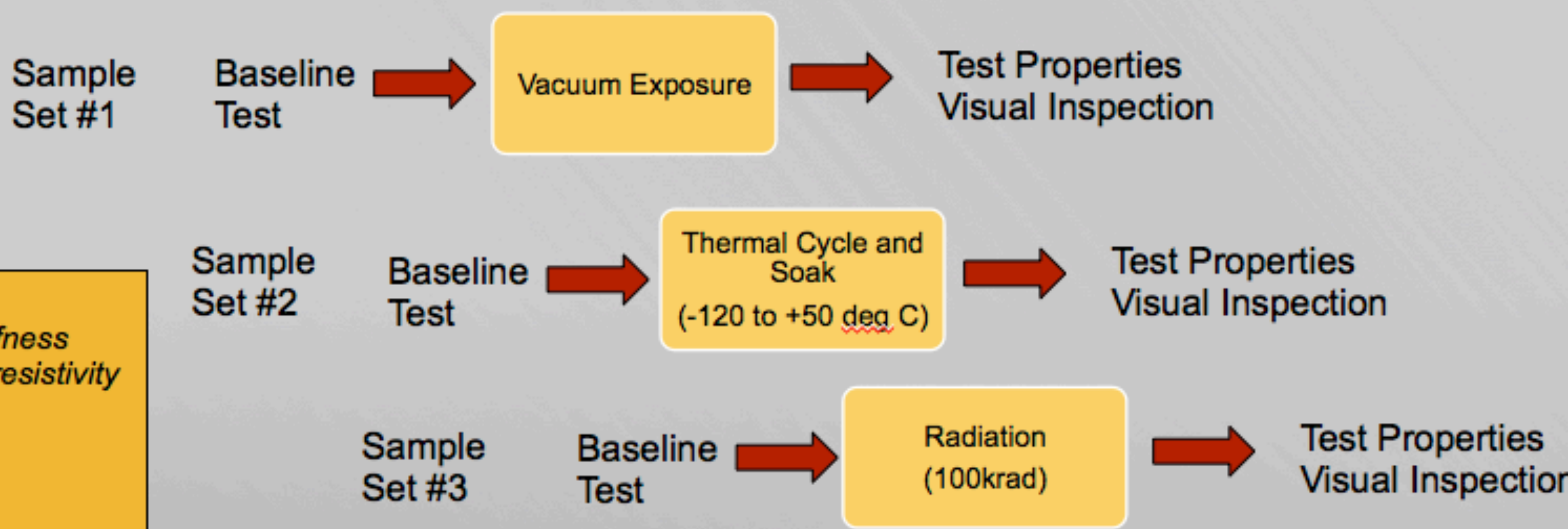


Test Protocol and Sequence

Option A – Sequential Exposure



Option B – Isolated Exposure



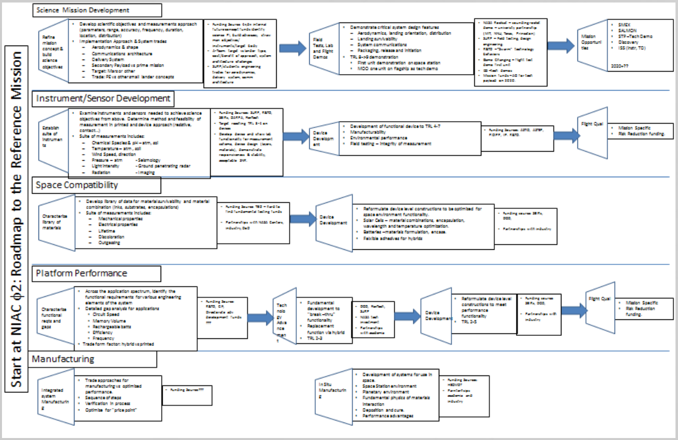
Properties to Test
- *Substrate stiffness*
- *Conductivity/resistivity*
- *Adhesion*
- *Functional*

Visible observations
- *Cracking*
- *Discoloration*

Roadmap Development

Generated roadmap to make the Reference Mission a reality.

- Accomplishments
  - Notional roadmap for the reference mission application laid out with advancement or study required, possible approach and potential funding source.



- Work to Go
  - Peer review and refine this roadmap
  - Generate roadmaps for other mission application
  - Develop a general investment strategy for Printed Electronics in Space.
  - Generate roadmaps by function:

    system technologies
    manufacturing
    component functionality
    instruments & sensors
    environments & materials

System Technologies	Manufacturing	Component Functionality	Instruments & Sensors	Environments
Swarm tasking and control	Intersystem compatibility	Data Storage	Micro-Fluidics	Radiation
Autonomy	Environmental Compatibility	Computation/Processing	Seismometry	Temperature ranges
Smart Networks	Printer qualification	Propulsion	Valving	Thermal cycling
Geo-location	Materials development (Graphene)	Energy Storage	Imaging	Micrometeoroid
Multiplexed Communication	Hybrid-manufacturing	Non-solar power sources	Spectroscopy	Planetary protection sterilization
Tracking		Mobility/Reconfigurability		Outgassing
Deployment/Support systems				Lifetime, Storage
				Atmospheric constituents

Summary

- Printed Electronics can offer great benefits to NASA applications whether its an entire spacecraft or a more focused application.
- We believe our NIAC task is contributing to accelerating its infusion.
- The development of the bench-top demonstrator has been highly successful! We are about one month away from having a fully integrated functional bench-top version of a Printed Spacecraft.
  - We already have plans in the work for a flight demonstration and the development of the Next Generation!
- A reference mission application has been developed along with its roadmap to flight.
- Environmental testing is imminent.
- The project has motivated many collaborations and synergy with other NASA programs!
  - Game Changing – EPSCoR – RockSAT – NASA Graduate Fellowship

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David Schwartz
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Janos Verdes

Boeing Team
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Thank You NIAC for the opportunity and inspiration!