NASA/TM-2013-217986/REV1

Flight Avionics Hardware Roadmap

Avionics Steering Committee

January 2014

September 2014

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Executive Summary

The results of the 2014 update of NASA's Avionics Steering Committee (ASC) Technology Roadmap are provided. This is the result of a multi-center effort directed by the ASC to address its stated goal "to advance the avionics discipline ahead of program and project needs". The NASA ASC is chartered out of the Office of Chief Engineer (OCE), and represents the Agency's avionics workforce through its line management representatives. The ASC Technology Roadmap is intended to strategically guide avionics technology development to effectively meet future NASA missions' needs. The roadmap addresses only flight avionics hardware and did not consider ground-based electronics, flight software, or ground software. It is understood that Centers, Directorates, Divisions, Offices, and other organizations may be independently engaging in road-mapping efforts with overlap to this ASC effort. Whenever possible we have attempted to draw from these other efforts in building this roadmap. The ASC recognizes the value of road-mapping at many levels and views these activities as synergistic.

The ASC Technology Roadmap looks out over 15+ years, with near-term focus on evolving technologies and a long-term look at technologies that are more revolutionary. This allows for a balanced push-pull technology portfolio and Technology Readiness Level (TRL) diversity. The roadmap is subdivided into two areas of enabling technologies (Foundational and Component) and four areas of subsystem-level technologies (*Command and Data Handling, Spaceflight Instrumentation, Communication and Tracking, and Human Interfaces*). Each of the Avionics subsystem-level technologies sections shows the advancement of key technologies to Technology Readiness Level TRL-6, at which point it is considered mature enough for infusion into a flight project to enable or enhance NASA Missions. To identify these key technologies an "80-percent solution" strategy was used. That is, technologies were identified that would meet on the order of 80-percent of defined NASA needs while high-cost technologies with limited utility to the broader NASA mission set were avoided. For the 2014 version of this roadmap, the mission set included those missions identified in the Global Exploration Roadmap as well as other unmanned missions not directly related to Exploration activities.

From the key technologies identified, a subset was selected for near term Agency investments. Factors considered in making this selection included readiness of the technology itself, potential for external partners to help develop it, and existing/future NASA technology development investments. The ASC's specific recommendations for near-term investments are:

1. Continue our investments in High Performance Computing, to provide direct dramatic improvements in flight functions and capabilities across the NASA mission classes, to enable new flight capabilities and mission scenarios, and to thus increase science and exploration return, while addressing the unique requirements and architectural features consistent with the energy efficiency and fault tolerance challenges of beyond-LEO, Earth-observing, and human spaceflight missions
    a. Rad Hard Multicore Processor
    b. Rad Hard High Capacity Memories – Volatile and Non
    c. Rad Hard High Speed Interconnect – multi mode (copper, fiber, wireless)

2. Work in conjunction with the NASA Electronic Packaging Program (NEPP) to provide advanced packaging technologies to support analog and digital electronics which are tolerant to both radiation and extreme temperatures (-200 to +200C)
3. Develop RFID/SAW-based wireless instrumentation systems to reduce the weight of spacecraft cabling infrastructure and increase reliability & accessibility of sensors
4. Conduct early spaceflight environmental testing on new light weight, low power 2D display technologies in order to influence commercial display manufacturing lines toward greater suitability for spaceflight
5. Develop a Radiation Tolerant Graphics Processing Unit (GPU) for use as the primary interface between crew and spacecraft data
6. Develop distributed/reconfigurable controller/sensor modules in spacecraft to reduce weight and increase reliability while also lowering non-recurring development costs
7. Develop mesh network protocols and standards for use in: space-to-space long-link systems with extreme propagation delays and outages; surface wireless systems with proximity-based quality of service and information assurance capabilities; and ad-hoc networking that can provide reliable end-to-end communications without carefully planned and scheduled link operations.
8. Develop a C&DH reference architecture which employs advances in Rad Hard High Performance Computing and Extreme Environment Electronics and deploy it in NASA "flat sats" and a flight demonstration project

In addition to the 8 investment recommendations above, the ASC has also identified future efforts "to advance the avionics discipline ahead of program and project needs":

- The ASC should engage with the 2014 Road-mapping teams to monitor and influence their Avionics-related content.
    - Ensure consistency with the ASC Roadmap
    - Provide analyses of deviations from the ASC Roadmap
- The ASC should establish a team to develop generic avionics-related use cases for both crewed and robotic missions and map ASC Roadmap milestones to them
- The ASC should partner with the Software SC and establish a joint working group to ensure coordination between their technology development efforts.
- NASA should actively monitor Radiation Hardened By Design (RHBD) programs and high density memory development programs conducted by other organizations with the intent to leverage their results for future NASA Component Technology development efforts.

Avionics Steering Committee (ASC) Membership

- Janet L. Barth/GSFC, ASC Chair
- Glenn A. Bever/DFRC, ASC Deputy Chair
- Kuok Y. Ling/ARC
- Timothy J. Ruffner/GRC
- Raphael R. Some/JPL
- Christopher J. Culbert/JSC
- Arnold T. Postell/KSC
- Arthur T. Bradley/LARC
- Kevin S. (Shawn) Wallace/MSFC
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Introduction

As part of NASA's Avionics Steering Committee's stated goal "to advance the avionics discipline ahead of program and project needs," the committee initiated a multi-Center technology road-mapping activity to create a comprehensive avionics roadmap. The roadmap is intended to strategically guide avionics technology development to effectively meet future NASA missions' needs.

All roadmaps represent a snapshot in time and are expected to evolve over time. This roadmap used the best available information from multiple sources to build a strategy for NASA's Avionics Steering Committee (ASC) which represents through its line management representatives the agency's avionics workforce chartered out of the Office of Chief Engineer (OCE). It is understood that Centers, Directorates, Divisions, Offices, and other organizations may be independently engaging in road-mapping efforts with overlap to this ASC effort. Whenever possible we have attempted to draw from these other efforts in building this roadmap. The ASC recognizes the value of road-mapping at many levels and views these activities as synergistic.

The approach taken by the road-mapping team was to focus on "the 80-percent solution," i.e., to identify technologies for NASA use that would meet on the order of 80-percent of defined NASA needs, specifically avoiding high-cost technologies with limited utility to the broader NASA mission set. The team also focused on developing a document that would inform, but not proscribe, future NASA technology development investments such as common avionics, high-performance space computing, or next generation spacecraft interconnect initiatives.

The scope of the roadmap aligns with the twelve avionics elements defined in the ASC charter, but is subdivided into two areas of enabling technologies (Foundational and Component) and four areas of subsystem-level technologies (*Command and Data Handling, Spaceflight Instrumentation, Communication and Tracking, and Human Interfaces*). *Foundational* Technologies comprise low-level fabrication and materials technologies (such as Complementary Metal-Oxide Semiconductor [CMOS] processes) and devices built on these technologies (such as transistors and Rad Hard By Design (RHBD) library elements). *Component Technologies are* built up from these devices (such as processors and memory chips) comprise the next category of technologies. Avionics subsystem-level technologies areas are enabled by and built from components. Avionics systems are considered to be mature enough for project infusion at Technology Readiness Level (TRL) 6. Projects can then utilize these systems to build capabilities that enable or enhance NASA missions.

The subsystem categories were those areas identified by the ASC charter as comprising "avionics." The road-mapping team analyzed each of the 14 Office of the Chief Technologist (OCT) Technology Roadmaps to identify technology needs in each of these areas to support future NASA projects and mapped them into these subcategories.

The roadmap looks out over a 15+ year period. The near term tends to focus on evolving technologies while longer-term technologies tend to be more revolutionary than evolutionary. This long-term view allows for a balanced push-pull technology portfolio and development strategy with broad TRL diversity. A long-term technology view also requires that the roadmap be revisited periodically as new and unforeseen breakthroughs occur, NASA's missions change, and funding profiles affect technology timelines.

This effort addressed only flight avionics hardware and did not consider ground-based electronics, flight software, or ground software. The decision to focus on flight avionics was driven by the following considerations:

1. General purpose ground-based electronics such as are used to support general design, test, and simulation activities will utilize state-of-the-art commercial-off-the-shelf products and there is no reason for NASA to track or invest in it as a technology area.
2. Ground computing that will benefit from utilization of the same electronic/avionics equipment that is used for flight systems, e.g., hardware-in-the-loop test beds, should be using the flight avionics chosen for the mission or mission set that they are supporting, and thus will be driven by the flight avionics that are the subject of this roadmap.

The roadmap takes Avionics Subsystem-Level Technologies to Technology Readiness Level (TRL) 6. At this point, Avionics systems are considered to be mature enough for project infusion. Projects can then utilize these systems to build capabilities that enable or enhance NASA missions as discussed below.

NASA Missions

Future NASA missions are the primary driver of avionics technology. As NASA missions move farther from Earth and become increasingly more complex, new challenges arise.

NASA's short-term strategy is to continue robotic exploration of the Moon, Mars, and NEAs. The Lunar Atmosphere and Dust Environment Explorer (LADEE) and the Mars Atmosphere and Volatile Evolution (MAVEN) missions launched in 2013, the Exobiology on Mars mission has a 2016 launch, and the Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer, mission is planning to launch an asteroid sample and return mission in 2016. Extremely challenging robotic missions (i.e., Mars Sample Return) are also being considered for the long term.

While robotic exploration continues, NASA will develop capabilities in support of human exploration to destinations such as the Moon, a NEA, and eventually Mars. Although NASA's Human Spaceflight portfolio is evolving, it is clear that reliability and autonomy will be key avionics drivers in any future mission set. Long-duration crewed missions as well as space-based observatories and solar system tours will require sophisticated reliability and fault tolerance. Furthermore, the communication delays and challenging orbital dynamics of NEA and extreme science missions require increased autonomy and on-board decision infrastructure. Traditional solutions to reliability and autonomy increase processing demands and redundancy which in turn drives system mass and power. Advanced technologies and approaches are needed to support these challenging missions.

These missions, characterized by long duration, vast distances, harsh environments, and in some cases the human element, require new avionics technologies to be developed to meet mission requirements for exploration and safely bring crews back to Earth. In the following sections, we identify the key technologies needed to support these missions and the time frames in which they are needed, or are expected to be available. Many of these technologies are anticipated to be developed by industry or other agencies e.g., Department of Defense, Department of Energy, and need only be monitored to track their progress and determine when they can be adopted for insertion into NASA missions. A minority of the technologies discussed below will require NASA investment to mature in a way that will be of use to NASA.

In the 2011 version of this roadmap, NASA's flexible capabilities-based approach was used as reference. For this 2014 update, NASA's contribution to the Global Exploration Roadmap (GER) was used as a reference point, along with additional NASA Robotics missions unrelated to the GER. For future versions, it is intended to develop a set of Avionics-related Use Cases which are generic to the specific Mission set of the time.

Initial Approach and 2014 Update

During the initial development of this roadmap (in 2011) Technology Areas were established by the ASC, and each area was assigned a lead. Each Technology Area lead formed a team composed of experienced personnel from around the Agency. Each team identified technologies which were both ready and needed. The assessment of need was based on the evaluation of the NASA Mission Set at that time. The assessment of readiness considered both the technology itself and the potential for external partners to help develop it. Technologies were identified that should be closely monitored by NASA, and in which investment is recommended in order that NASA's unique requirements be met. Existing/planned NASA technology development investments in the areas of Common Avionics, High-Performance Space Computing, and Next Generation Spacecraft Interconnects were also considered.

For the 2014 ASC Roadmap Update, new leads assigned to update each section. They were asked to review, re-validate and re-prioritize the technology milestones in their respective areas. As the team worked through this activity, it was decided to split the Foundational Technologies section into sections for both Foundational and Component technologies. This led in turn to a shift of technology milestones from the Command and Data Handling section into the Component section, and significant content updates to all three. Minor content updates were made to the other technology sections, and an attempt was made to show completed technology milestones. Additionally, an effort was made to identify dependencies between technology milestones in different areas of the Roadmap.

Highly visible changes were also made to the document format. These are meant to enhance the organization and presentation of the content. These changes include the addition of an Executive Summary and a Results and Recommendations section, a restructuring and revision of other introductory content, a new graphics format, and the use of a "baseball card" format for all technology milestones to ensure consistency throughout.

Finally, it was decided to use NASA's contribution to the Global Exploration Roadmap (GER) as a reference point, along with additional NASA Robotics missions unrelated to the GER.

Results and Recommendations

The Updated 2014 ASC Roadmap has 122 identified technology milestones, 58 of which are complete or targeted for completion within 5 years, with an additional 23 to be completed by 2020. These are shown on a timeline in Figure 1. A corresponding timeline is provided for each technology area in the following sections.

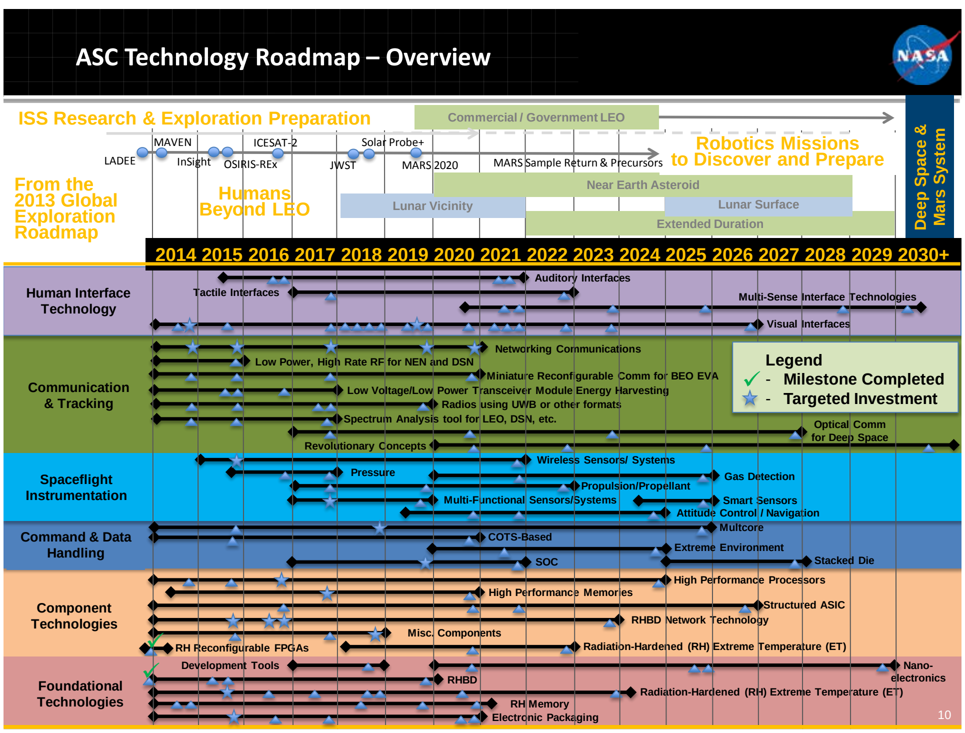

Figure 1. Overview Roadmap

Each technology area also has a prioritized list of recommended investments and other recommendations. These are distilled into a set of ASC investment recommendations and other recommendations below.

Specific Recommendations for Near-Term Investments

1. Continue our investments in High Performance Computing, to provide direct dramatic improvements in flight functions and capabilities across the NASA mission classes, to enable new flight capabilities and mission scenarios, and to thus increase science and exploration return, while addressing the unique requirements and architectural features consistent with the energy efficiency and fault tolerance challenges of beyond-LEO, Earth-observing, and human spaceflight missions
   a. Rad Hard Multicore Processor [Ref C01]
   b. Rad Hard High Capacity Memories – Volatile and Non [Ref C04]
   c. Rad Hard High Speed Interconnect – multi mode (copper, fiber, wireless) [Ref C08, C09, C10]
2. Work in conjunction with the NASA Electronic Packaging Program (NEPP) to provide advanced packaging technologies to support analog and digital electronics which are tolerant to both radiation and extreme temperatures (-200 to +200C) [Ref F04, F14]
3. Develop RFID/SAW-based wireless instrumentation systems to reduce the weight of spacecraft cabling infrastructure and increase reliability & accessibility of sensors [Ref I06]
4. Conduct early spaceflight environmental testing on new light weight, low power 2D display technologies in order to influence commercial display manufacturing lines toward greater suitability for spaceflight [Ref H08, H25]
5. Develop a Radiation Tolerant Graphics Processing Unit (GPU) for use as the primary interface between crew and spacecraft data [Ref C13]
6. Develop distributed/reconfigurable controller/sensor modules in spacecraft to reduce weight and increase reliability while also lowering non-recurring development costs [Ref I08]
7. Develop mesh network protocols and standards for use in: space-to-space long-link systems with extreme propagation delays and outages; surface wireless systems with proximity-based quality of service and information assurance capabilities; and ad-hoc networking that can provide reliable end-to-end communications without carefully planned and scheduled link operations. [Ref CT01, CT02, CT03, CT04, CT05]
8. Develop a C&DH reference architecture which employs advances in Rad Hard High Performance Computing and Extreme Environment Electronics and deploy it in NASA “flat sats” and a flight demonstration project [Ref CD01, CD04]

Other Recommendations for future efforts

- The ASC should engage with the 2014 Road-mapping teams to monitor and influence their Avionics-related content.
- Ensure consistency with the ASC Roadmap
- Provide analyses of deviations from the ASC Roadmap
- The ASC should establish a team to develop generic avionics-related use cases for both crewed and robotic missions and map ASC Roadmap milestones to them
- The ASC should partner with the Software SC and establish a joint working group to ensure coordination between their technology development efforts.

- NASA should actively monitor Radiation Hardened By Design (RHBD) programs and high density memory development programs conducted by other organizations with the intent to leverage their results for future NASA Component Technology development efforts.

Detailed recommendations from each technology area are captured in the remaining sections of the document.

Foundational Technologies

Foundational technologies comprise the fundamental fabrication processes and materials systems used to implement hardware avionics components. Primarily, we are concerned with radiation hardened and extreme temperature capable semiconductor technologies, and with high density and extreme temperature capable microelectronics packaging technologies. We will not attempt to roadmap commercial technologies; these roadmaps are readily available from industry associations, e.g. the Semiconductor Industry Association (SIA). Instead, this section focuses specifically on those technologies that are uniquely of interest to space based avionics. As will be seen in the following paragraphs, modern commercial semiconductor technologies can provide sufficient radiation and temperature tolerance to minimize, or in some cases eliminate, the need for custom radiation hardened technologies if appropriate design guidelines are used. The recent spate of Radiation Hardened By Design (RHBD) technologies are actually custom circuit element libraries, formulated with strict adherence to specific guidelines that are meant to be fabricated with commercial semiconductor processes. Similarly, advanced packaging technologies for space avionics are based on their commercial equivalents but with specific design and usage guidelines tailored to the space environment.

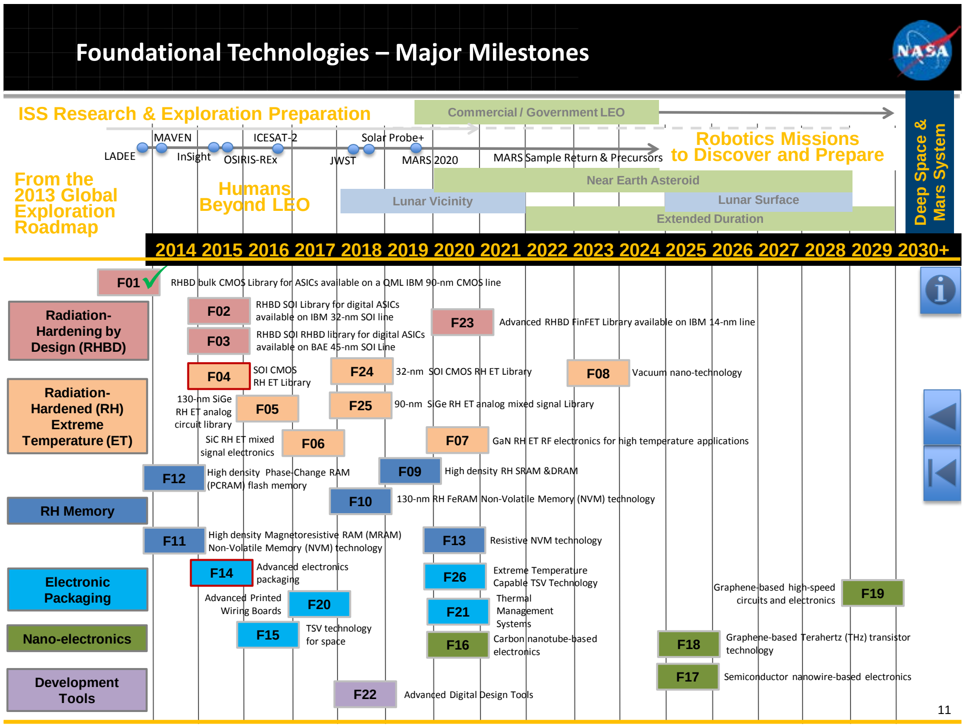

Figure 2: Foundational Technologies – Major Milestones

Radiation Hardening by Design (RHBD)

<table>
<tr><td colspan="3">F01: RHBD bulk CMOS Library for digital Application-Specific Integrated Circuits (ASICs) available on a QML IBM 90-nm CMOS line</td></tr>
<tr><td>Priority:
High</td><td>Target Date:
2013</td><td>Benefit: Provides radiation hard ASICs using commercially available advanced bulk CMOS process technology.</td></tr>
<tr><td colspan="3">Description: A Boeing-developed RHBD 90-nm bulk CMOS standard cell library was originally funded by the Defense Threat Reduction Agency (DTRA) and the Defense Advanced Research Projects Agency (DARPA). The library provides the capability to develop radiation-hardened digital ASICs on a commercial semiconductor fabrication line. Aeroflex has qualified the 90nm RHBD standard cell library in 2013 and a QML-certified line for 90nm RHBD ASICs is being implemented with multiple product assurance levels available, such as QML Q and V, military and industrial, radiation hardened from 100krads(Si) to 1Mrads(Si). This roadmap item was completed in 2013.</td></tr>
<tr><td colspan="3">Dependencies: None</td></tr>
</table>

F02: RHBD Silicon-On-Insulator (SOI) Library for digital ASICs available on IBM 32-nm SOI CMOS line **F03: RHBD SOI RHBD library for digital ASICs available on BAE 45-nm SOI CMOS Line**		
Priority: **High**	*Target Date:* **2015** **2015**	*Benefit:* Provides radiation hard ASICs using commercially available advanced SOI CMOS process technology.
Description: DTRA has also initiated a follow on 32-nm RBHD program utilizing the IBM 32nm SOI CMOS process with a target completion date of 2015. Similar efforts are ongoing at other companies, with BAE taking the lead, under NRO funding, in the development of a 45-nm RHBD library built on the IBM 45-nm SOI CMOS line with a target completion date of 2015. NASA should monitor these programs. NASA does not need to invest in these RHBD semiconductor technologies, though additional funding could be used to accelerate development schedules, to influence the types of cells to be developed, the testing to be performed, and the selection and fidelity of the development vehicles to be designed/validated. However, NASA can use these standard cell libraries and associated tools to develop ASICs and standard products at reduced costs, compared to previous approaches.		
***Dependencies*: None**		

F23: Advanced RHBD FinFET library available on IBM 14-nm CMOS Line		
Priority: **High**	*Target Date:* **2020**	*Benefit:* Provides radiation hardness ASICs using commercially available advanced FinFET process and technology.
Description: Advanced non-classical CMOS such as multiple gate MOSFET including FinFET transistor structure is predicted to be cornerstone of the sub-20nm technologies. Program focusing on the development of the RHBD library on the FinFET technology can be expected and estimated to be available in 2020 time frame. NASA should monitor these programs. NASA does not need to invest in these RHBD semiconductor technologies, though additional funding could be used to accelerate development schedules, to influence the types of cells to be developed, the testing to be performed, and the selection and fidelity of the development vehicles to be designed/validated. However, NASA can use these standard cell libraries and associated tools to develop ASICs and standard products at reduced costs, compared to previous approaches.		
***Dependencies*: None**		

Radiation Hardened (RH) Extreme Temperature (ET)

F04: Digital and analog SOI CMOS RH ET Library for extreme high and low temperature applications **F24: 32-nm SOI CMOS RH ET Library for extreme high and low temperature application**		
Priority: **High**	*Target Date:* **2015** **2018**	*Benefit:* The development of extreme temperature capable, radiation hardened electronics would obviate the need for thermal management systems in many future spacecraft, with a potential savings in spacecraft power and mass while providing greatly enhanced flexibility in spacecraft configuration and design.
Description: Digital ASICs, with possible extension in some environments to mixed-signal ASICs, based on SOI CMOS and RHBD libraries, have the potential to operate beyond the military standard temperature range of -55°C to 125°C, as well as to provide radiation hardness. CMOS and SOI CMOS have been demonstrated to generally work well at low temperatures with faster speed and lower leakage current, and SOI CMOS has been demonstrated to work at well over 200°C, but work is required to determine operational characteristics over the wider temperature ranges and to develop design rules, tools, and possibly circuit library modifications to enable wider temperature operation and reliability. This will require NASA to work with the Defense Threat Reduction Agency (DTRA) to invest and utilize the capabilities, while leveraging the RHBD standard cell libraries and associated tool sets for radiation hardness only NASA requires.		
***Dependencies*: None**		

F05: 130-nm SiGe RH ET analog circuit library for extreme low temperature applications **F25: 90-nm SiGe RH ET analog circuit library for extreme low temperature applications**		
Priority: **High**	*Target Date:* **2016** **2018**	*Benefit:* Enables electronics for extreme low and wide temperature range applications, obviating the need for thermal management systems in many future spacecraft, with a potential savings in spacecraft power and mass while providing greatly enhanced flexibility in spacecraft configuration and design.
Description: 0.5um SiGe extreme temperature radiation-hardened analog ASICs exhibiting radiation hardness to 300 kilorads (krad) and capable of operation over a temperature range of at least -140°C to 125°C have been demonstrated for motor control systems capable of operating for long lifetimes in the Mars environment (-135°C to 85°C). With limited life expectancy of the IBM 0.5um semiconductor fab line, a next-generation SiGe extreme temperature RH technology in 130 and 90 nm would provide additional capability, reduced power, and long-term availability of the technology. A recommended target date for completion of a 130-nm and 90-nm SiGe RH ET technology is 2016 and 2018, respectively, to support a broad range of future missions including Extra-Vehicular Activity (EVA), primitive bodies, and future Mars missions.		
***Dependencies*: None**		

F06: Silicon carbide (SiC) RH ET mixed signal electronics for high temperature application **F07: Gallium nitride (GaN) RH ET radio frequency electronics for high temperature applications**		
Priority: **High**	*Target Date:* **2017, 2020**	*Benefit:* Enables electronics for extreme high temperature applications and provides potential mass savings for power conversion.
Description: SiC and GaN have been demonstrated as potential technologies for RH high temperature, low integration-density applications beyond 300°C. There have been many process and reliability improvements as well as design enhancements in these technologies during the past years that position them as the most promising candidates for both high power conversion applications such as solar electric power and high temperature applications such as in situ mission to Venus. NASA investment is required to enhance radiation hardness for SiC technology. Currently, the limitation of the SiC and GaN technologies is that the number of transistors per chip is limited to approximately 100, and thus, the technologies are being used for power converters, digital small scale integration (SSI) and simple analog functions. Additional NASA investment is necessary if increased integration density is to be developed to enable complex more complex electronics. A recommended target date for these technologies is 2017 to 2020 time frame to be available for future planetary and asteroid missions.		
***Dependencies*: None**		

F08: Vacuum nano-technology		
Priority: **Low. Low TRL**	*Target Date:* **2023**	*Benefit:* Provides rad-hard electronics for extreme high temperature applications.
Description: A new class of vacuum nanoelectronics components demonstrated recently are both radiation insensitive and extremely high temperature tolerant (>700℃) making them suitable for extreme environment applications. These devices use nanotubes or nanowires integrated with microstructures and together with nanoelectronics should be available for extreme environment electronics applications between 2020 and 2025.		
***Dependencies*: None**		

Radiation Hardened Memory

F09: High density RH Static (SRAM) and Dynamic RAM (DRAM) technologies		
Priority: **High**	*Target Date:* **2019**	*Benefit:* Provides rad hard high density memory.
Description: One-time-programmable Programmable Read-Only Memories and Metal-Nitride-Oxide-Silicon electrically Erasable PROMs have been used in space applications since the 1990s. Today, RH high-density memories utilizing more advanced memory technologies are needed for space systems to provide improved power utilization at orders of magnitude increase in density (which translates to mass, volume, and complexity reduction). SRAM is typically not radiation hardened device unless special designs and processes are implemented. Currently, rad-tolerant SRAMs are available from BAE and Honeywell. DRAM is also sensitive to both TID and SEE. System architecture needs to be designed to minimize effects of Single Event Functional Interrupts (SEFI), multi-bit errors, etc., while ECC and memory scrubbing need to be used to minimize effects of Single Event Upsets (SEU), stuck bits and other soft errors to improve DRAM's reliability. With Synchronous DRAM (SDRAM), Double Date Rate (DDR), DDR2, DDR3 technologies, space-avionics designs are beginning to use the new DRAM technologies which requires comprehensive and yet quick evaluations of the technologies especially from the radiation perspectives. As for non-volatile memory technologies, FeRAM, MRAM, PCRAM, and Resistive RAM, provide improved density and power utilization with improved radiation tolerance. These memory cell technologies will, however, still require RH CMOS control logic, which can be provided by RHBD technologies with minimal impact to overall component power or density. Currently, radiation hardened CMOS SRAM, SONOS and PCRAM are available as volatile and non-volatile memory options up to 16-Mb per die. AFRL is planning a multi-year program to develop such memory technologies and associated memory components starting in 2014. NASA should monitor this program and consider co-developing some of these technologies in order that NASA unique requirements are met, e.g., extreme temperature capability, power management and fault tolerance. If NASA invests in RH ET technologies as recommended previously, then there will be a strong desire for ET memory technologies as well. This is an extremely challenging requirement and will require significant NASA investment as the most dominant and straightforward memory technology for future missions is likely to be Embedded DRAM (e-DRAM), which is not capable, at the present time, of exhibiting extreme temperature tolerance. This is an area where NASA investment can yield high return on investment.		
***Dependencies*: None**		

F10: 130-nm Ferroelectric RAM (FeRAM) Non-Volatile Memory (NVM) technology		
Priority: **Medium** Density is relatively low.	*Target Date:* **2018**	*Benefit:* Provides rad hard non-volatile memory.
Description: Non-volatile memory devices have traditionally relied on floating gate technology. Floating gate flash memory technology has been dominating the non-volatile memory market for the past 25 years. There are a number of emerging technologies based on new materials and/or storage concepts. Ferroelectric RAM (FeRAM) is a random access memory using ferroelectric material as its storage cell or capacitor. The charges in DRAM capacitor discharge when power is off, while the ferroelectric material maintains polarity even without power, and thus DRAM is volatile memory and FeRAM is NVM. The density is relatively low currently at 4Mb per die. The current technology is 130-nm. The Ferroelectric thin films comprising the memory elements are inherently resistant to ionizing radiation, but its control circuitry may not be. The level of radiation hardness of FeRAM depends on the CMOS processes and designs utilized for the control circuitry other than the FeRAM cell itself. Using RHBD approaches, a rad-hard FeRAM was demonstrated up to 1Mrad and SEL tolerance to greater than 75 LET in and a rad-tolerant stackable FeRAM was also demonstrated.		
***Dependencies*: None**		

F11: 65-nm Magnetoresistive RAM (MRAM) Non-Volatile Memory (NVM) technology		
Priority: **Medium** Density is relatively low.	*Target Date:* **2014**	*Benefit:* Provides rad hard non-volatile memory.
Description: Magnetoresistive Random Access Memory (MRAM) has been under development since the 1990s. The current mainstream MRAM is so called Spin-Transfer Torque (STT) MRAM, as it applies spin-aligned ("polarized") electrons to directly torque the domains by using a thin layer of MgO for the Magnetic Tunneling Junction (MTJ). Similar to FeRAM, radiation hardness of MRAM can be achieved by the use of RHBD for its control circuitry. The density is relatively low at 1Mb to 16Mb per die depending on radiation hardness level. The current technology node is 65-nm.		
***Dependencies*: None**		

F12: 32-nm Phase-Change RAM (PCRAM) flash memory		
Priority: **Medium** Density is relatively low.	*Target Date:* **2014**	*Benefit:* Provides rad hard non-volatile memory.
Description: Phase-change RAM (PRAM) exploits the unique behavior of chalcogenide glass. With the application of heat produced by the passage of an electric current, this material can be "switched" between two states, an ordered, crystalline phase having lower electrical resistance and a disordered, amorphous phase with much higher electrical resistance. PCMs are available from a number of manufacturers. There is a family of the rad-hard PCM type memory modules called C-RAM (Chalcogenide-base RAM) available from BAE Systems, which is designed specifically for the radiation environments encountered in spacecraft applications. The density is relatively low currently at 4Mb to 512Mb per die depending on radiation hardness level. The current technology node is 32-nm.		
***Dependencies*: None**		

F13: Resistive NVM technology		
Priority: **Medium**. Low TRL.	*Target Date:* **2020**	*Benefit:* Potentially provides rad hard, high density non-volatile memory.
Description: Resistive random-access memory (RRAM) bears some similarities to PCM, but explore a different side of the materials. Instead of using a heat source to change the phase of the materials, a sufficiently high voltage/current is applied to a dielectric layer to create a conduction path. The conduction path formation can arise from different mechanisms, and different forms of RRAM have been disclosed, based on different dielectric materials. The RRAM technologies are at relatively low technology readiness level and will require investment to mature them into reliable and manufacturable technologies.		
***Dependencies*: None**		

Electronic Packaging

F14: Advanced electronics packaging		
Priority: **High**	*Target Date:* **2015**	*Benefit:* Potential 10x improvement in mass, volume and power of spacecraft avionics, potential 2x or greater improvement in system reliability due to reduction of interconnect elements.
Description: There are several advanced packaging technologies that would improve mass, volume, and power of spacecraft avionics. Candidate technologies include: stacked chips/packages/modules, high density interconnect, and chip-on-board technologies. Guidelines and design rules for use in space environments, as well as qualification requirements and procedures, need to be developed for a minimal but optimum subset of available commercial packaging technologies. Once this is done, qualification of this optimal subset can proceed. This is not a traditional technology investment, but an adaptation and qualification of existing commercial/military technologies, and should be coordinated with programs such as the NASA Electronic Parts and Packaging Program (NEPP). Recommended target date is 2015 to support Mars 2020, Europa, and future science and exploration missions, all of which will benefit from the volume and mass reduction of these advanced packaging technologies.		
***Dependencies*: None**		

F15: Through Silicon Via (TSV) chip stack technology for space qualification and applications **F26: Extreme Temperature (ET) capable TSV technology for space qualification and applications**		
Priority: **High**	*Target Date:* **2016** **2020**	*Benefit:* Potentially 50x improvement in mass, volume and power of spacecraft avionics, potential 10x improvement in system reliability due to reduction of interconnect elements and improved thermal management.
Description: TSV chip stacks allow direct stacking of silicon chips with metalized vias placed anywhere throughout the chip. This basic technology, developed by the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, is currently available from several commercial vendors. It provides the ability to develop a series of stackable integrated circuits that can be mixed and matched as necessary to provide required capability. The advantage here is that due to extremely short distances and low capacitance of interconnect, the stack essentially operates as a single chip with all the power and speed advantages inherent in monolithic systems. Additionally, due to elimination of single chip packaging and interconnect, volume and mass are reduced and reliability increased. The technology is being developed for commercial use, but NASA use requires extension of the technology to extreme temperatures and across multiple semiconductor processes, e.g., SOI CMOS and SiGe. Recommended target date is 2016 for TSV and 2020 for ET TSV to support future missions including EVA and small/micro-satellites for all exploration and science missions. The current 'sweet spot' in chip stacking technology is the 2.5D stack. Unlike 3D stacking, in which 5 or 6 layer silicon die are stacked, 2.5D stacks a single layer of chips onto a silicon interposer using TSV interconnects. The advantage of 2.5D stacks is that multiple small (low cost/high yield) die can		

packaged with extremely low inter-die impedance and thus many of the advantages of a single monolithic die, but at significantly lower cost and higher yield. Another advantage of 2.5D packaging is the ability to combine die from dissimilar materials and processes, e.g., SiGe and SOI CMOS, into a single, quasi-monolithic structure. 2.5D utilizing TSV interconnects on as Si substrate is seen as the logical next step to full 3D stacked electronics and may be a sweet spot for future NASA avionics systems.
***Dependencies*: None**

F20: Advanced Printed Wiring Boards		
Priority: **High**	*Target Date:* **2017**	*Benefit:* Advanced printed wiring board design and fabrication techniques are necessary to enable future high performance computing systems, both with their high-pin count packages and fast switching speeds.
Description: With increased clock frequencies and miniaturization, some challenges are present to existing packaging approaches. Complex devices such as FPGAs and processors are moving to larger packages with large pin counts. These devices drive the printed wiring board designs to increased layer count and thickness, as well as decreased pitch between pins. Both of these can significantly increase the difficulty of producing highly reliable printed wiring boards. Compounding this is the need to place discrete components very close to the device pins for the purpose of signal conditioning. To address these problems, advances will be needed in printed wiring board layout and fabrication techniques for spaceflight applications. Specifically, broader use of embedded passive within printed wiring boards would be advantageous.		
Dependencies: None		

F21: Thermal Management Systems		
Priority: **Medium**	*Target Date:* **2020**	*Benefit:* Active thermal management can allow increased power density that may be inherent in some future onboard processing systems.
Description: With higher performance devices and increased miniaturization, thermal management at the box, board, and device level will be an increasing challenge. To address this, active thermal management technology that can be efficiently and cost effectively integrated into these assemblies is needed for the most challenging applications. To be truly effective, active thermal management must be straightforward to integrate with electronics assemblies. It must also be sufficiently reliable such that it will not significantly degrade overall system reliability.		
Dependencies: None		

Nano-Electronics

F16: Carbon nanotube-based electronics		
Priority: **Medium. Low TRL for avionics**	*Target Date:* **2020**	*Benefit:* Offers extraordinary material choice to develop flexible, transparent and inherent radiation-hardened electronics that potentially can shrink the entire avionics and system electronics volume by an order of magnitude.
Description: Nano-electronic technology, including carbon nanotube, semiconductor nanowire and graphene-based electronic technologies, are promising candidates to sustain the relentless progress in scaling for electronic devices. Carbon nanotube-based transistor technology has been realized as single-electron carbon nanotube transistors at room temperature and ballistic carbon nanotube field-effect transistors. However, carbon nanotube-based transistors have not yet been demonstrated the capability of integrating into logic-gate circuits with densities comparable to CMOS technology, due to the lack of technology for mass production.		
***Dependencies*: None**		

F17: Semiconductor nanowire-based electronics		
Priority: **Medium. Low TRL for avionics**	*Target Date:* **2025**	*Benefit:* Offers extraordinary material choice to develop flexible, transparent and inherent radiation-hardened electronics that potentially can shrink the entire avionics and system electronics volume by an order of magnitude.
Description: Nanowire-based electronics is still at a very low technology readiness level. However, they may complement or replace carbon nanotube-based electronics in some applications for the next generation of computing devices. For example, a NAND logic gate with undoped silicon nanowires was demonstrated in 2012.		
***Dependencies*: None**		

F18: Graphene-based Terahertz (THz) transistor technology **F19: Graphene-based high-speed circuits and electronics**		
Priority: **Medium. Low TRL for avionics**	*Target Date:* **2025, 2029**	*Benefit:* Offers extraordinary material choice to develop flexible, transparent and inherent radiation-hardened electronics that potentially can shrink the entire avionics and system electronics volume by an order of magnitude.

Description: With nanowire and nanotube field-effect transistors, as well as graphene-based 300GHz transistors having been demonstrated, the nanotechnology roadmap projects THz transistor technology by 2020, and graphene-based high-speed circuits and electronics by 2028. Nanowire, nanotube and/or graphene-based ASICs are projected to replace silicon-based electronics in future electronic systems and can be applied in most applications, such as digital, photonics, analog, and mixed-signal. Fundamentally, these nano-technologies offer higher levels of integration and lower power through smaller transistors and higher electron mobility than is achievable in silicon-based technologies. They also offer inherent radiation hardness and robustness to environmental stresses. Graphene is a mono-layer or one-atom-thick sheet of carbon. It offers high electron mobility and radiation hardness at extremely small feature size and thus low power. Transistor-equivalent structures have been built using stacked (mono) layers of graphene and separating dielectrics, but deposition and patterning methods suitable for large-scale manufacturing have not yet been developed. Carbone nanotube and semiconductor nanowire technologies promise extremely high conductivity wiring both on-chip and off, but suitable mass manufacturing technologies have not yet been developed. Investment by NASA will be required to tailor these technologies and devices to NASA's unique requirements, but as these technologies are not yet at TRL3, it is not clear what investments will be required to meet NASA needs.
***Dependencies*: None**

Development Tools

F22: Advanced Digital Design Tools		
Priority: **Medium**	*Target Date:* **2018**	*Benefit:* Advanced digital design tools will enable complex systems to be implemented quickly and cost effectively, while at the same time having the fault tolerance to operate reliably in the space environment.
Description: As technology scales to smaller fabrication processes, higher clock speeds, and greater miniaturization, design tools will need to adapt. While the commercial industry will provide much of this adaptation, some specific tools are of particular interest for NASA applications. In the realm of digital design, tools for logic simulation, synthesis, and place-route will need to accommodate larger designs, newer FPGA devices, structured ASIC platforms, and newer standard cell ASIC libraries. Key to NASA applications, these tools will need to incorporate single event mitigation and advanced fault tolerance techniques, especially as the required techniques will likely grow in complexity and device feature sizes are reduced. To reduce development costs, there is a need for tools allowing digital designs to be specified at a higher level of abstraction (as compared to current hardware design languages), but still develop highly efficient and reliable hardware.		
Dependencies: None		

Component Technologies

Component technologies constitute the electronic parts utilized in building avionics subsystems. While it is often the case that the foundational technologies discussed in the previous section are utilized in fabricating these components, this is not always true. Commercial components are often flown in spacecraft avionics systems for a variety of reasons, including: unavailability of equivalent components built from radiation hard technologies, acceptability of reliability levels of commercial components in the application environment, ability to adapt the system/mission to accommodate commercial component performance and reliability levels. There is, however a significant cost incurred when using commercial components in space system: cost of up-screening, reduction in system performance and reliability, mass penalty for radiation and thermal accommodation. In this section, we focus on critical components that either are or could be fabricated using the technologies discussed in the foundational technologies section.

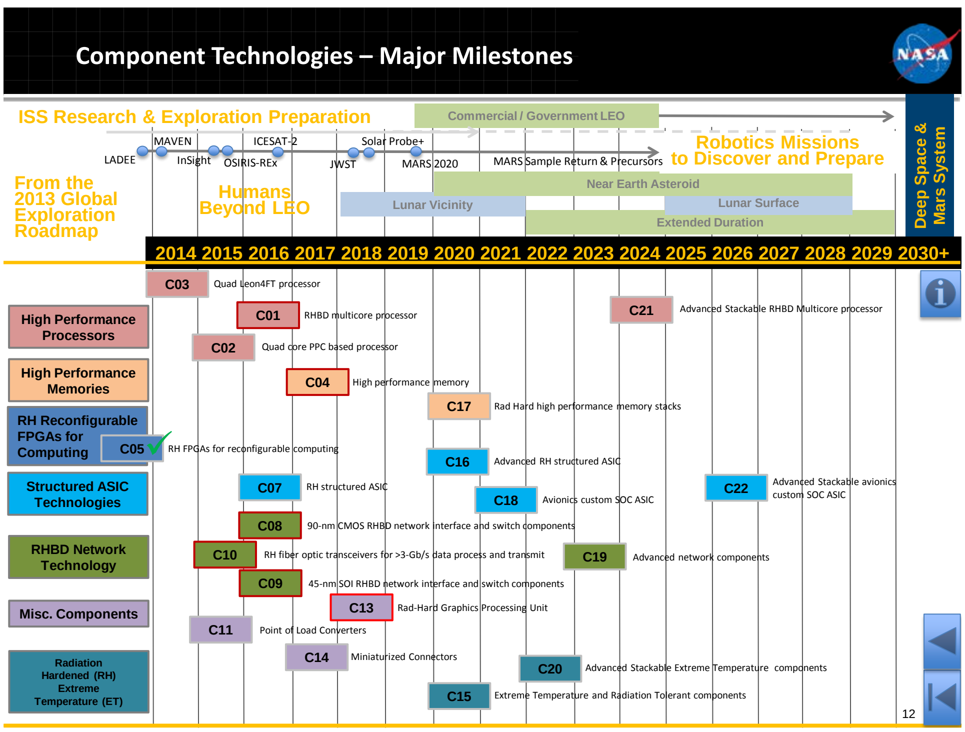

Figure 3. Component Technologies – Major Milestones

High Performance Processors

C01: RHBD multicore processor		
Priority: **High**	*Target Date:* **2016**	*Benefit:* Enhanced performance over the existing selection of Rad Hard space processors enabling more autonomous operations and science processing onboard.
Description: The NRO OPERA program, utilizing the 90nm RHBD foundational technology, developed a 49 core processor based on the commercially available Tilera Tile64 processor. The Maestro processor contains 49 general purpose processor cores, four high speed Double Data Rate (DDR) 2 memory ports, four 10 Gigabits Per Second (Gb/s) XAUI Input/Output (I/O) ports as well as Gigabit Ethernet and GPIO ports and is similar to a cluster computer architecture on a single chip. While this processor has been incorporated into several board-level products for evaluation and software development, it is not applicable, in general, to NASA missions due to a lack of power management and fault tolerance capabilities. It does, however, serve as a proof of principle, illustrating that a high performance processor chip can be developed at reasonable cost and provides a pathfinder for development of future high performance processors suitable for space-based system. A second-generation machine in either 90-nm CMOS RHBD, or in 32-nm SOI CMOS RHBD, based on the Maestro architecture and compatible with the Maestro software suite, would support a broad range of NASA missions and be relatively easily inserted into future missions. Depending on technology selection and levels of power management and fault tolerance included, it could be available at TRL6 in the 2013-15 time frame. Such a machine would be greatly enhancing, if not be enabling, for Mars Sample Return, Asteroid/Comet Sample Return, NEA, and human and human-robotic precursor missions. It is unclear at this time if NRO will go forward with such a development activity, but if NRO elects to develop such a machine, NASA should consider teaming with NRO in this development in order to ensure that NASA unique requirements, e.g., power management and fault tolerance, are provided. A joint NASA-AFRL funded effort to define an optimal processor architecture for future NASA missions is currently under way. The NGSP/HPSC project, if successful, will be followed by a processor development project that will culminate in a high performance multicore processor suitable for both USAF and NASA missions in the 2017 time frame. If NRO goes forward with a next generation Maesto processor, and if suitable accommodation can be made for USAF and NASA requirements, then the two projects may be combined. If the NRO does not go forward with a next generation Maestro, then the current NGSP/HPSC investment should be continued. The advent of RHBD technology opens the door for many organizations to develop advanced processors and similarly complex digital components at much reduced costs compared to previous technologies.		
***Dependencies*: F02, F03, F14**		

<table>
<tr><td colspan="3">C02: Quad core PPC based processor</td></tr>
<tr><td>Priority:
Medium</td><td>Target Date:
2015</td><td>Benefit: Leverages on the existing RAD750 allowing for reuse of knowledge and code developed for the RAD750 while providing higher performance.</td></tr>
<tr><td colspan="3">Description: NRO is also funding a four core PPC based processor development at BAE, utilizing BAE’s 45nm SOI CMOS RHBD process. While this processor provides as significant advance over the current single core RAD750, it is does not have sufficient throughput for the most demanding NASA applications and has minimal power management and fault tolerance capability. It also requires more power than is anticipated to be required for a more capable multicore processor in 32nm SOICMOS. NASA should monitor this development, but investment is not recommended at this time.
BAE is also developing a SIMD streaming data co-processor utilizing the 90nm CMOS RHBD technology. This processor is expected to be used in conjunction with the four core PPC processor described above. The combination of the two processors, with required memory and ancillary components is expected to require75 to 100W, however, which puts it out of the range of most NASA programs. Investment is not recommended.</td></tr>
<tr><td colspan="3">Dependencies: F03</td></tr>
</table>

<table>
<tr><td colspan="3">C03: Quad Leon4FT processor</td></tr>
<tr><td>Priority:
High</td><td>Target Date:
2015</td><td>Benefit: The four processors along with supporting components, such as spacewire, will be on a single ASIC allowing for a powerful platform in a small package and using low power.</td></tr>
<tr><td colspan="3">Description: Aeroflex corp plans to develop a four-core LEON4 Fault Tolerant processor utilizing the 90nm CMOS RHBD technology acquired from Boeing. The LEON4 will utilize a 64 bit data bus and will provide a substantially faster platform on a single System on a Chip than a RAD750 board. No investment from NASA is required.</td></tr>
<tr><td colspan="3">Dependencies: F01</td></tr>
</table>

<table>
<tr><td colspan="3">C21: Advanced Stackable RHBD Multicore Processor</td></tr>
<tr><td>Priority:
High</td><td>Target Date:
2024</td><td>Benefit: Order of magnitude improvement in performance, and performance/watt with 3-5x reduction in size.</td></tr>
<tr><td colspan="3">Description: Utilizing advances in semiconductor and packaging foundational technologies, this is a next generation version of C01 in 14nm FinFET utilizing TSV technology for stackability.</td></tr>
<tr><td colspan="3">Dependencies: F23, F14, F15</td></tr>
</table>

High Performance Memories

C04: High performance memory (2017)		
Priority: **High**	*Target Date:* **2017**	*Benefit:* High performance memory will enable high performance computing as well as other subsystems.
Description: There is a long-standing need for radiation hardened, high capacity, low power, high speed, volatile/nonvolatile memories. To date there has been no solution to this need other than the use of commercial components with the concomitant risks, costs and compromises engendered thereby. As in processor component technology, NASA has unique needs in this area that will most likely require NASA investment in order to fulfill. As mentioned in the Foundational Technologies section, AFRL plans to start a rad hard memory program in 2014 with the intention of developing several different types of memory to meet the broad range of subsystem needs. In order to ensure that NASA-unique power management and fault tolerance capabilities are capabilities are provided, NASA should invest in a partnership with AFRL in this program.		
***Dependencies*: None**		

C17: Rad Hard High Performance Memory Stacks		
Priority: **High**	*Target Date:* **2020**	*Benefit:* Memory stacks increase density, reduce power/mass/volume and improve performance of memory systems and will be required for practical future applications of both high performance computing and SOC based avionics systems.
Description: Development of TSVs and chip stacking technology applied to memory allows many variations of stacked systems from individual memory stacks to memory embedded in heterogeneous stacked systems to memory array chips stacked with memory controller chips. In all cases the stacking of die provides significant performance, power, mass, volume benefits at moderate chip-level cost increases with significant system level cost reduction.		
Dependencies: F04, F15		

Radiation Hardened (RH) Reconfigurable FPGAs for Computing

C05: RH FPGAs for reconfigurable computing		
Priority: **High**	*Target Date:* **2013**	*Benefit:* Reconfigurable FPGAs allow for changes to the HW design in flight, for multiple configurations depending on the mission phase, and the ability to correct errors at a much lower cost than burn once FPGAs.
Description: Radiation-hardened and extreme temperature-capable FGPAs for use in avionics systems, both as single function implementation vehicles and as core elements in reconfigurable computing are required to meet the processing throughput, flexibility, fault tolerance, and power-to-performance levels desired for future NASA spacecraft. These components can be developed by utilizing RHBD libraries and processes from several sources. Radiation-hardened devices, fault-tolerant architectures, reusable cores, development tools and practices, and validation and integration standards are needed for reconfigurable computing for space system applications. These deficiencies translate to technology gaps in the reconfigurable computing development path from the FPGA-based reconfigurable machines of today to more general morphware-based machines of tomorrow. In overcoming these gaps, technology developments in fault tolerance, system-on-chip architectures, design-time tools and reconfigurable hardware run-time systems, and re-usability via integration standards and system modularity are required. In addition to standard FPGA architectures, higher level reconfigurable architectures are highly desirable as they provide the ability to work at higher levels of integration at reduced power for a given level of performance. Instead of working at the virtual gate or look-up table level, these devices work at the compute-element level, allowing higher power efficiency and simplified design. As with FPGAs, they need to be implemented in 90-nm and below RHBD technologies. Given the high cost of developing FPGAs (the Xilinx QV5 SIRF cost upwards of $30M and was never fully rad hardened), and the difficulty of engaging commercial companies to rad harden their products, it is recommended that NASA monitor and encourage companies already providing rad tolerant FPGAs to continue advancing their product line and specifically to engage AFRL and Xilinx in discussions aimed at upgrading the QV5. In addition to radiation hardening, it would also be useful, in an upgraded part, to improve temperature tolerance		
***Dependencies*: None**		

Structured ASIC Technologies

C07: RH structured ASIC		
Priority: **Medium**	*Target Date:* **2016**	*Benefit:* A structured ASIC is an intermediate technology between ASIC and FPGA, offering high performance and low cost. Using a Structured ASIC allows projects to develop designs quickly and at lower costs than with a typical ASIC design
Description: RH structured ASICs are becoming available today. These components can survive extreme environments, provide quick turn around, and be procured at relatively low cost for digital and mixed-signal ASICs (they may not be as radiation hardened or as extreme temperature capable as SOI or SiGe RHBD ASICs, but they are significantly lower cost, faster turnaround, and suitable for a broad range of missions). With additional investment by NASA, development of additional configurations of structured ASICs, as well as additional extreme temperature characterization of these devices can be provided by the companies currently developing these components. This technology is included in the 2014 SBIR call and is expected to mature a digital and mixed signal structured ASIC component within 2-3 years		
***Dependencies*: None**		

C16: Advanced Rad Hard Structured ASIC		
Priority: **High**	*Target Date:* **2020**	*Benefit:* A structured ASIC is an intermediate technology between ASIC and FPGA, offering high performance and low cost. Using a Structured ASIC allows projects to develop designs quickly and at lower costs than with a typical ASIC design. This is an advanced version of C07 providing order of magnitude increase in capability at similar SWaPC
Description: RH structured ASICs are becoming available today. These components can survive extreme environments, provide quick turn around, and be procured at relatively low cost for digital and mixed-signal ASICs (they may not be as radiation hardened or as extreme temperature capable as SOI or SiGe RHBD ASICs, but they are significantly lower cost, faster turnaround, and suitable for a broad range of missions). With additional investment by NASA, development of additional configurations of structured ASICs, as well as additional extreme temperature characterization of these devices can be provided by the companies currently developing these components. This technology is included in the 2014 SBIR call and is expected to mature a digital and mixed signal structured ASIC component within 2-3 years. This is an advanced version that will provide enhanced capability for future s/c and could likewise be included in an SBIR call.		
Dependencies: None		

C18: Avionics Custom SOC ASIC		
Priority: **High**	*Target Date:* **2021**	*Benefit:* Custom ASIC implementing a complete avionics system on a chip will provide an extremely small, low cost, medium performance, avionics system for small spacecraft as well as the basis for a new class of distributed avionics systems.
Description: A single ASIC, based on 32nm RHBD/RHET libraries, comprising all required elements of a small avionics system, stackable with memory, and with the ability to de-power unneeded functions, will provide the basis for both small spacecraft avionics systems as well as distributed avionics systems for larger spacecraft, rovers, landers, and other platforms. In addition to providing the basis for a distributed system, it also enables a new class of extremely low cost, high performance fault tolerance through massive inclusion of available "cold spared" subsystems.		
Dependencies: F02, F24, F14, F15		

C22: Advanced Stackable Avionics Custom SOC ASIC		
Priority: **High**	*Target Date:* **2026**	*Benefit:* Order of magnitude improvement in performance, and performance/watt with 3x reduction in size for small/medium performance avionics systems.
Description: Utilizing advances in semiconductor and packaging foundational technologies, this is a next generation version of C01 in 14nm FinFET utilizing TSV technology for stackability.		
Dependencies: F23, F14, F15		

Radiation Hardening by Design (RHBD) Network Technologies

C08: 90-nm CMOS RHBD network interface and switch components **C09: 45-nm SOI RHBD network interface and switch components** **C10: RH fiber optic transceivers for >3-Gb/s data process and transmit**		
Priority: **High**	*Target Date:* **2016, 2016, 2015**	*Benefit:* Higher performance network technology will allow for distributed systems, for high performance computing, and better science being collected. They also enable highly capable crewed vehicles and habitats.
Description: Future NASA space missions will require extremely high bandwidth spacecraft interconnect systems. The venerable 1 Megabit Per Second (Mb/s) 1553 is being superseded by 250-Mb/s SpaceWire and, in the Human Exploration and Operations Mission Directorate (HEOMD), by the upcoming 1-Gb/s Time-Triggered Gigabit Ethernet (TTGbE) standard. Next generation missions, however, with multi-gigabit instruments, onboard science, and autonomy processing, will require multi-gigabit interconnect bandwidth as well as real-time determinism, fault tolerance, power/bandwidth scalability, and seamless interoperability between copper, fiber optic, and wireless physical (phy) media layers. Host data transmission modes including broadcast/multicast/point-to-point, and synchronous/asynchronous will also be required. Several standards for space systems are likely to emerge, including time-triggered 10-gigabit ethernet, a space version of Serial Rapid I/O, and Space Fiber (aka SpaceWire-2). The Next Generation Spacecraft Interconnect System (NGSIS) committee is developing one such standard with participation from NASA, the Air Force Research Laboratory, Space and Missile Command, the National Reconnaissance Office (NRO), the Naval Research Laboratory, the American Institute of Aeronautics and Astronautics, VITA, Lockheed Martin Aerospace Corp., Boeing Corp., British Aviation Electronics, Honeywell Corp., and others. Network interfaces, routers, switches, and endpoints supporting these protocols, as well as Serializer/Dererializers and phy-layer transceivers are expected to be forthcoming from space avionics and component vendors, most likely implemented in 90-nm and below RHBD technologies. There is a concern that, as in the past, offerings from multiple vendors will not be interoperable. The NGSIS is attempting to ensure interoperability by virtue of a tight specification and validation criteria that guarantee interoperability, but NASA will need to invest resources to ensure that these standards meet unique NASA requirements as well as to ensure both interoperability and ease of use of component offerings. NGSIS V1.0 is expected to be ratified in early 2014 – due to a desire to maintain close compatibility with COTS Rapid I/O, this version is not expected to have all of the desired features that NASA would like for HEOMD and SMD mission, but will provide a basis for future versions that will be more closely aimed at NASA's unique needs. A version 2.0 of the NGSIS spec should be targeted for 2016 Copper interconnect at these speeds is relatively well understood, but difficult to achieve in radiation hardened and extreme temperature capable versions with the desired isolation, fault tolerance, and power management features that are available in fiber optic. Fiber optic implementations, however, do not provide extreme radiation and temperature tolerance, while copper wire implementations are not well suited to longer transmission distances and do not offer good isolation at high frequency. Radiation hardened fiber optic phy-layer technology is progressing to the point where it is a viable		

alternative to copper in many spacecraft systems. Radiation tolerance of 100 krad has been achieved with data rates of >3 Gb/s over hundreds of meters in extremely small packages with easy assembly, and good tolerance of temperature, vibration, and shock. In addition to reducing power and providing electromagnetic interference-free operation and electrical isolation, this phy-layer medium can provide transparent and seamless chip-to-chip, board-to-board, and box-to-box interconnect. NASA investment is required to meet NASA's unique requirements (radiation, shock, vibration, temperature, long life, high reliability). The recommended target date is 2014 to support future high data rate science instruments and exploration missions. This need is being addressed via an SBIR expected deliver rad tolerant 10Gb/s fiber optics in 2014. Wireless interconnect phy-layer is not being addressed. Wireless interconnect offers a host of advantages in NASA missions, eliminating the mass, power, and unreliability of cables and connectors, providing ease of integration and test, and allowing simpler reconfiguration, sparing, fault tolerance, and retrofitting of systems. NASA support will be required to develop a wireless standard compatible with the advanced protocol(s) currently under development and interoperable with wire and fiber optic based systems. This technology should be targeted at the generation after next of HEOMD and SMD spacecraft, i.e., approx. 2022.
***Dependencies*: C08 & C09 - F01, F02, F03, F04; C10 - None**

C19: Advanced Network Components		
Priority: **High**	*Target Date:* **2023**	*Benefit:* Will provide extremely high bandwidth, real time capable, highly reliable, low power interconnect for future space systems.
Description: A stackable chip set or chip set comprising network interface, switching/routing, fault tolerance and power management functions providing on the order of 10Gb/s per lane, 40Gb/s per channel. This is planned as a next generation upgrade to C09, C10.		
Dependencies: F23, C09, C10, F14, F15		

Miscellaneous Components

C11: Point of Load Converters		
Priority: **High**	*Target Date:* **2015**	*Benefit:* More efficient power converters will reduce loss in the system and allow us to use smaller solar panels and be lighter weight while reducing thermal loads.
Description: Point of Load Converters provide regulated and filtered power to the local electronics, typically at board level. They are the interface between the power subsystem and the avionics subsystem. Due in part to technology issues, but also to component lead times and design practices, currently available converters, as implemented in NASA spacecraft tend to be extremely inefficient, dissipating as much as half their power as heat, large and bulky, as well as unreliable and costly. High efficiency, radiation hardened point of load converters with high efficiency, low mass and volume and high long term efficiency are needed for future spacecraft avionics. In addition, an intelligent converter that can monitor its load for fault conditions and report its status to the spacecraft computer would be quite valuable. Currently, no such converts are known to exist. NASA should invest in this component technology.		
***Dependencies*: None**		

C13: Rad-Hard Graphics Processing Unit		
Priority: **High**	*Target Date:* **2018**	*Benefit:* A Rad Hard Graphics Processing Unit is required to support HEOMD crewed missions incorporating large complex displays.
Description: There currently exist two distinct types of GPUs. The original GPU designs provided accelerated graphics rendering for displays, as indicated by their name –these are relatively simple, low power, medium complexity devices and are readily available in industry. Over the past few years, researchers have found that the underlying architecture of these graphics processing units can be exploited to provide extremely high speed computation of certain types of algorithms. These new GPUS have become extremely large, complex, power intensive and expensive. The devices addressed here are of the former type - simple, relatively low cost, low power graphic rendering units for use in crewed vehicle displays.		
***Dependencies*: F01, F02, F03**		

C14: Miniaturized Connectors		
Priority: **Medium**	*Target Date:* **2017**	*Benefit:* Highly reliably miniaturized connectors with improved impedance matching are essential to implementing future miniaturized C&DH and processing systems.
Description: Connectors have historically been a weak link in system reliability, where a misconnection on a single pin can have catastrophic effects. Many commercial connectors incorporate mechanical designs that do not have the inherent robustness for high reliability systems operating in harsh environments. Increased signal frequencies of emerging onboard networks will require improved impedance matching, while still maintaining reliability. For small C&DH systems, the size of the connectors can often be the pacing element that determines the degree of miniaturization that can be achieved. Here, miniaturized (yet reliable) connectors with high pin counts are needed.		
Dependencies: None		

Radiation Hardened (RH) Extreme Temperature (ET)

C15: Extreme Temperature and Radiation Tolerant Components		
Priority: **High**	*Target Date:* **2020**	*Benefit:* Space qualifiable, extreme temperature (-200 to +200C) tolerant electronics will dramatically reduce spacecraft thermal management requirements and enable deep space small spacecraft missions, enhance EVA and habitat reliability and capabilities
Description: Approximately 20% of spacecraft mass and power is devoted to thermal management. Future small sat missions will not have the mass or power budget to implement thermal management systems. SOICMOS, SiGe, and other emerging technologies can provide analog, digital and mixed signal electronic components capable of long life, high performance, and low power that are able to tolerate these extreme temperature regimes. New packaging technologies such as chip on board, TSVs and advanced PWB technologies can provide long life under extreme temperature and thermal cycle conditions. These emerging technologies provide the opportunity to greatly minimize the thermal management requirements on future missions, allowing reduction in mass, power, cost unreliability/vulnerability, while greatly enhancing mission/spacecraft design flexibility and option space. Proof of principle devices have been fabricated and tested showing viability of the underlying fundamental technology. NASA should invest in developing an avionics component set for small spacecraft, EVA suits, spacecraft external electronics, and in-situ instruments. Specific components in this suite will include: 1)Cold Remote Engineering Unit – a two chip set capable of tolerating extreme cold and serving as an interface/data concentrator node for spacecraft external sensors such as temperature and strain gauges 2)Cold Microcontroller – a microcontroller suitable for use as a spacecraft-external instrument and subsystem control 3) Hot analog chip containing amplifiers, current and voltage references/sources and switches/multiplexer capable of operation to 300C, 4) Hot Microsequencer capable of operation to 300C.		
Dependencies: F04, F05, F06		

C20: Advanced Stackable Extreme Temperature Components		
Priority: **High**	*Target Date:* **2022**	*Benefit:* Extremely low power, mass, volume avionics component suite capable of operation at extreme temperature as well as radiation levels. This is a next generation advance to C15.
Description: Utilizing advances in semiconductor and packaging foundational technologies, this component suite provides a stackable suite of components at the next generation semiconductor nodes (90nm SiGe, 32nm SOICMOS, 14nm FinFet). These components will be capable of operation from -200C to +200C and at least 300krad. Specific Components will include: 1) Processor – a multicore processor suitable for small to medium size spacecraft/missions, 2) medium density, low power volatile and nonvolatile memories, 3) multi-voltage output point of load converter, 3) mixed signal ADC/DAC and analog I/O. Additional components for use in extremely high temperature operation (up to 300C) will include 4) mixed signal ADC/DAC and analog I/O, 5) microcontroller		
Dependencies: F06, F07, F24, F26		

Command and Data Handling Technologies

The command and data handling (C&DH) system serves as the onboard intelligence for a spacecraft. Typical C&DH functions include command decoding and distribution, stored command execution, telemetry collection formatting and downlink, subsystem control (attitude control system, power system, etc.), and detection and handling of onboard fault conditions. The C&DH system may also perform instrument data processing, although that function is often performed within the instrument itself. C&DH systems span a wide range of size, mass, and performance. For large missions, the C&DH system may be implemented in a number of enclosures (each containing multiple boards) interconnected via a high-speed onboard network. Smaller missions may implement the entire C&DH function on a single board, while future miniaturized spacecraft will implement the C&DH function on a single System-On-a-Chip (SOC). Still further in the future, 3D integrated packages using TSVs may implement C&DH systems with an even greater degree of miniaturization.

Several architectural considerations and options influence the implementation of a C&DH system. Perhaps the most prominent architectural choice is the degree to which C&DH is centralized or distributed. Options range from implementing the entire C&DH function within a single enclosure, to implementing it in a small number of enclosures, to migrating processing into many of the subsystems and instruments. Choices will ultimately influence mass, power, reliability, and ease of integration. However, the optimal selection is very much dependent on mission needs.

Another architectural choice is the pedigree of the components used to implement the C&DH function. On one end of the spectrum, the system can be implemented with spaceflight qualified components which offer higher reliability and radiation tolerance, but often at the cost of reduced performance and higher cost and lead time. On the other end of the spectrum, COTS parts can be used. This option may offer increased performance and reduced lead times, but at the cost of questionable reliability and radiation tolerance. Some existing and emerging C&DH systems employ COTS components, but “manage” them with qualified components. Examples include the SpaceCube, the CHREC Space Processor (CSP), and Proton series of single board computers from SpaceMicro. It should be noted however, that these architectures incur a cost of increased complexity in order to manage the COTS components.

Another key architectural option is the type of processor to be used. While the C&DH function typically requires a general purpose processor (GPP), there may be specific functions for which a digital signal processor (DSP) may be optimal. Discrete components are available for both GPPs and DSPs, although there can be limitations on interoperability between specific selections of these processors. Another option can be to implement either or both of these processing functions within an FPGA. Here, soft-core processors and peripheral logic can be instantiated within the fabric, and DSP functions can be implemented directly in FPGA logic resources. There are limitations in soft-core processor performance, and implementing DSP functions in FPGA logic can be a labor intensive task.

To reduce C&DH system cost, development schedule, and risk, interoperability of various C&DH elements is highly advantageous. Achieving this at the box level necessitates standard onboard network interfaces, allowing boxes from different developers to be efficiently integrated. Standard network interfaces such as SpaceWire, and TT-Gig-E exist, but improved performance is needed for future C&DH systems. Additionally, standard board-level interfaces (both mechanical and electrical) can allow boxes to be implemented with board level products from different developers. The same principles for interoperability exist at the chip level, where standard on-chip interconnect busses can enable IP cores from various developers to be seamlessly integrated.

As a higher level system, the C&DH is implemented with the components and foundational technologies described in previous sections of this roadmap. The C&DH requires software to perform its functions, and hence the roadmap described here must be consistent Agency plans for Software technology development.

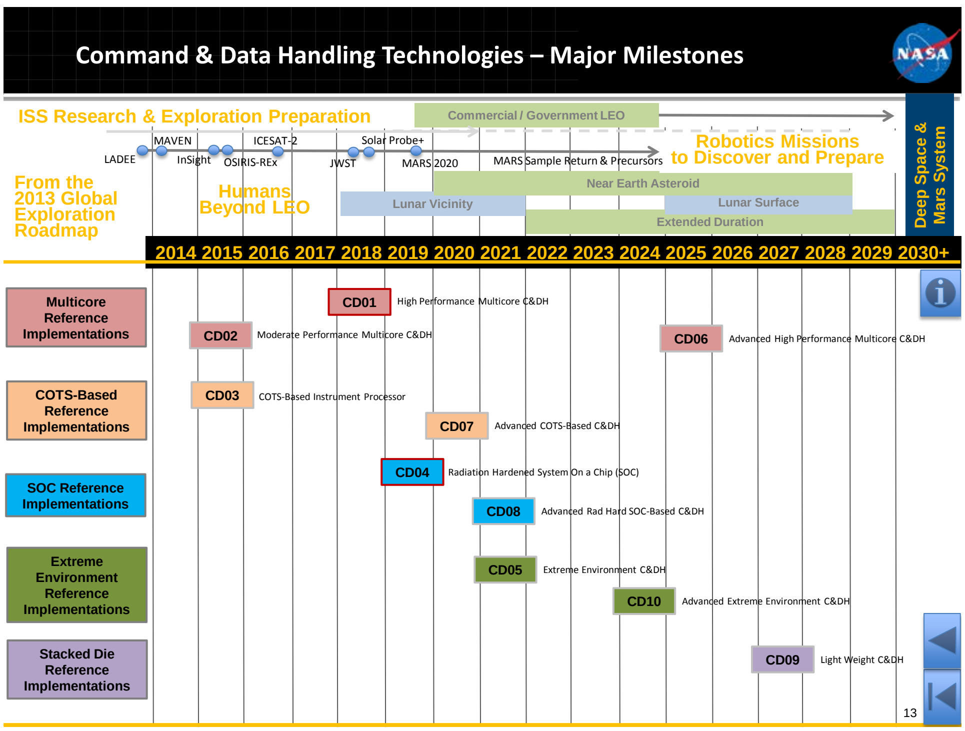

Figure 4. Command & Data Handling Technologies – Major Milestones

Multicore Reference Implementations

<table>
<tr><td colspan="3">CD01: High Performance Multicore C&DH</td></tr>
<tr><td>Priority:
High</td><td>Target Date:
2018</td><td>Benefit: A multicore based C&DH subsystem will enable high performance onboard processing applications including autonomous landing systems and high data rate instruments. The inherent flexibility of a multicore processor will allow this subsystem to be applied to a broad range of mission applications.</td></tr>
<tr><td colspan="3">Description: Future large missions with requirements for high performance onboard computing will benefit from C&DH subsystems based on radiation hardened multicore processors, with 16 or more general purpose processor cores. Typical missions would include; (a) explorer-class to flagship robotic spacecraft, (b) large surface rovers, and (c) crewed spacecraft. C&DH systems for these missions, likely implemented as box (or multiple box) solutions, central to which would be a board with a multi-core processor, memory (with suitable radiation tolerance, performance, and capacity), and network interfaces capable of handling both high-rate instrument data and low-rate control traffic. To accommodate varying computing demands of specific applications, it would be advantageous for the C&DH system to be expandable to accommodate multiple processor devices, and to also accommodate a reconfigurable FPGA or DSP coprocessor. The high-performance multicore C&DH should have sufficient fault isolation and containment to allow both non-mission-critical sensor processing and mission-critical spacecraft processing to be performed within a single processor device.
For human-safety-critical applications in crewed missions, an even greater degree of fault isolation and containment will be required. This may require the C&DH to allow redundancy and voting at the processor device or board level.</td></tr>
<tr><td colspan="3">Dependencies: C01, C04, C09, C10, C11, CD06</td></tr>
</table>

Processor Implementation	"Manycore" General Purpose Processor (16+ Cores)	
Performance	24 GOPS, 10 GFLOPS (without coprocessor device)	
Memory	16-32 Gb DDR3/4, NV-RAM	
Interfaces	Multiple 10Gbps Network Interfaces, TBD Low-Rate Legacy Interfaces	
Power	~ 15W	

CD02: Moderate Performance Multicore C&DH		
Priority: **Medium**	*Target Date:* **2015**	*Benefit:* This type of C&DH subsystem will provide performance beyond the current state with power dissipation reduced to the extent that it could be used for smaller missions.
Description: Smaller missions in the future with more modest requirements for onboard computing will benefit from C&DH subsystems based on radiation hardened multicore processors with reduced power and improved performance (with respect to the current state of the art). Typical missions would include; (a) SmallSat to small-explorer class robotic spacecraft, (b) small surface rovers, and (c) spaceflight instruments. C&DH systems for these missions, implemented either as a board or a box, could be based on a processor with more modest performance and fewer cores. Alternatively, this C&DH could be implemented with a manycore processor with only a few cores utilized (to reduce power consumption).		
Dependencies: C02, C03, C11		

Processor Implementation	Multicore General Purpose Processor (4+ Cores)	
Performance	5 GOPS, 2 GFLOPS (without coprocessor device)	
Memory	4-8 Gb DDR3/4, NV-RAM	
Interfaces	Multiple 10Gbps Network Interfaces, TBD Low-Rate Legacy Interfaces	
Power	~ 5W	

CD06: Advanced High Performance Multicore C&DH		
Priority: **Medium**	*Target Date:* **2025**	*Benefit:* As requirements for onboard autonomy processing and instrument data processing increase for future missions, an advanced high performance multicore based C&DH subsystem will provide the necessary processing capability. The inherent flexibility of a multicore processor will allow this subsystem to be applied to a broad range of mission applications.
Description: To meet future onboard processing needs, the advanced high performance multicore C&DH will leverage processor devices with increased number and performance of processing cores, memory devices with increased capacity and performance, and onboard networks with higher throughput. This represents the next generation beyond the C&DH capabilities described in CD1, but retains the emphasis on fault tolerance and power management. However, the methodologies to attain fault tolerance and power management will be adapted to accommodate newer integrate circuit designs and processes.		
Dependencies: C17,C19,C21		

Commercial Off the Shelf (COTS)-Based Reference Implementations

CD03: COTS-Based Instrument Processor		
Priority: **Medium**	*Target Date:* **2015**	*Benefit:* This C&DH offers the ability to leverage the improved performance of emerging COTS devices for a subset of applications that can tolerate an increased upset rate.
Description: Applications exist that may utilize a C&DH subsystem which utilizes COTS devices with reduced levels of reliability pedigree and radiation tolerance. These applications include some cubesat and smallsat missions that can accept a higher level of mission risk. Additionally, these subsystems may also have use as onboard computers for some science instruments where transient faults are not mission critical. These systems can employ commercial devices with higher performance than radiation tolerant devices, but at the cost of including hardened circuitry to "manage" unhardened commercial devices. To implement these C&DH systems, there is a continuing need to characterize the radiation performance and upset characteristics of emerging processor devices (frequently reprogrammable FPGAs), and then design and test board level solutions that include hardware and software to mitigate upsets in those devices. Efficient application development tools are also needed.		
Dependencies: C05, CD06		

Processor Implementation	COTS FPGA (Xilinx Virtex-7 or Equivalent)	
Performance	2 GOPS (Embedded Processor), 50+ GOPS (Logic Fabric)	
Memory	16-32 Gb DDR3/4, SRAM, NV-RAM	
Interfaces	Multiple 10Gbps Network Interfaces, TBD Low-Rate Legacy Interfaces	
Power	~ 15W	

CD07: Advanced COTS-Based Instrument Processor		
Priority: **Medium**	*Target Date:* **2020**	*Benefit:* As COTS computing devices evolve to provide higher performance and more advanced features, an advanced COTS-based C&DH offers the ability to leverage these devices for a subset of applications that can tolerate an increased upset rate.
Description: Applications exist that may utilize a C&DH subsystem which utilizes COTS devices with reduced levels of reliability pedigree and radiation tolerance. These applications include some cubesat and smallsat missions that can accept a higher level of mission risk. Additionally, these subsystems may also have use as onboard computers for some science instruments where transient faults are not mission critical. These systems can employ commercial devices with higher performance than radiation tolerant devices, but at the cost of including hardened circuitry to "manage" unhardened commercial devices. As is the case with C&DH system outlined in CD3, there is a continuing need to characterize the		

radiation performance and upset characteristics of future processor devices via ground based radiation testing. Only with this testing can board level solutions be developed that include hardware and software to mitigate upsets in those devices. As a follow on to CD3, this C&DH subsystem will utilize future generations of COTS devices.
Dependencies: None

System On a Chip (SOC) Reference Implementations

CD04: Radiation Hardened System On a Chip (SOC) Based C&DH		
Priority: **High**	*Target Date:* **2019**	*Benefit:* A hardened SOC would be broadly applicable across smaller mission classes that require high reliability, miniaturization, and reduced power. Additionally, this could be a valuable building block for distributed C&DH systems.

Description: For SmallSat missions and instruments requiring improved reliability and mission life (beyond existing COTS approaches), C&DH systems implemented with radiation hardened SOC solutions is an ideal approach. Additionally, these devices can enable distributed C&DH systems for many classes of missions, which can increase performance, contain faults to a subsystem, and lower power by turning on processors only as needed. Miniaturization and reduced power dissipation are provided by the SOC architecture, and implementation on a radiation hardened platform provides the reliability suitable for longer missions and potentially harsh environments. Future radiation hardened FPGAs, structured ASICs, or standard cell ASICs are viable an implementation platforms for these devices. While some minimalist C&DH subsystems may be implemented with only the SOC device itself, an architecture must be developed where higher level SOC-based C&DH subsystems can be developed that incorporate external devices such as data converters, larger memory devices, and physical-level drivers for onboard networks.

Dependencies: C07

Processor Implementation	SOC Implemented in Radiation Hardened FPGA or Structured ASIC	
Performance	200 MIPS	
Memory	512Mb - 1Gb SRAM, NV-RAM	
Interfaces	Medium Rate Network Interface, TBD Low-Rate Legacy Interfaces	
Power	~ 1W	

CD08: Advanced Radiation Hardened System On a Chip (SOC)		
Priority: **Medium**	*Target Date:* **2021**	*Benefit:* A hardened SOC would be broadly applicable across smaller mission classes that require high reliability, miniaturization, and reduced power. Additionally, this could be a valuable building block for distributed C&DH systems.
Description: As advanced structured ASICs, FPGAs, and standard cell ASICs are developed with increasing clock speeds and capacity, advanced radiation hardened SOCs can implement C&DH systems with expanded functionality and performance for "lightweight" applications such as smallsats, miniaturized instruments and subsystems. With respect to CD4, CD8 will implement a broader and more complete set of C&DH functions onto a single device. However, even with the increased SOC functionality, an architecture is needed where higher level SOC-based C&DH subsystems can be developed that incorporate external devices such as data converters, larger memory devices, and physical-level drivers for onboard networks.		
Dependencies: C16		

Extreme Environment Reference Implementations

<table>
<tr><td colspan="3">CD05: Extreme Environment C&DH Subsystems</td></tr>
<tr><td>Priority:
Medium</td><td>Target Date:
2021</td><td>Benefit: C&DH subsystems with modest performance that can operate in extreme radiation and thermal environments can enable missions to be deployed to destinations previously deemed inaccessible. Furthermore, on more typical missions these extreme environment systems can significantly reduce or eliminate the resources required for thermal management.</td></tr>
<tr><td colspan="3">Description: Two variants of extreme environment C&DH subsystems are planned, one for each temperature extreme. For extreme cold, a subsystem based the remote engineering unit and microcontroller identified in C15 would be developed. Such a subsystem would be consistent with requirements for operation at outer planets, or on permanently shadowed regions of the lunar surface. For the hot extreme, a subsystem based on the hot analog chip and microsequencer would be developed. Such a subsystem would be consistent with requirements for operation on the surface of Venus. Beyond the devices specified in C15, the subsystems here would include the packaging, interconnect, and any ancillary components required to implement a complete C&DH.</td></tr>
<tr><td colspan="3">Dependencies: C15</td></tr>
</table>

<table>
<tr><td colspan="3">CD10: Advanced Extreme Environment C&DH Subsystems</td></tr>
<tr><td>Priority:
Medium</td><td>Target Date:
2024</td><td>Benefit: Advanced C&DH subsystems with modest performance that can operate in high radiation and extreme thermal environments (hot AND cold) can enable missions to be deployed to destinations previously deemed inaccessible. Furthermore, on more typical missions these extreme environment systems can significantly reduce or eliminate the resources required for thermal management.</td></tr>
<tr><td colspan="3">Description: Beyond the capabilities of the C&DH subsystems specified in CD6, this subsystem provides the capability to operate at both extreme hot and extreme cold. These environments can be expected on the lunar surface and on surfaces of NEOs. Beyond the stacked extreme environment devices specified in C20, the subsystems here would include the packaging, interconnect, and any ancillary components required to implement a complete C&DH.</td></tr>
<tr><td colspan="3">Dependencies: C20</td></tr>
</table>

Stacked Die Reference Implementations

CD09: Light Weight C&DH Subsystem		
Priority: **Low**	*Target Date:* **2027**	*Benefit:* Implemented with 3D integrated circuits, a light weight C&DH subsystem with modest performance can be implemented in a single package. These miniaturized C&DH systems can be used for very small spacecraft, and miniaturized data processing systems for instruments and subsystems.
Description: Future C&DH subsystems will be implemented with 3D integrated packages using through silicon vias (TSVs) to achieve improved miniaturization, power efficiency, and performance. With this technology, systems can be implemented by stacking individual die or wafers and interconnecting them with TSVs. To enable NASA C&DH systems to be implemented with this technology, there is a need for architectures that allow die from different developers and different fabrication processes to be integrated into a single assembly. For example, a processor could be implemented in one process, while memory, and network interfaces could be implemented on different die in the stack and fabricated with entirely different processes. Additionally, there is a need for methodologies to ensure the reliability and testability of the individual die, the TSVs, and the integrated 3D packages. To enable the development of 3D ICs, advanced mixed-mode modeling and simulation tools will be needed to allow device level simulation. These tools would provide an integrated environment capable of co-simulation of complex systems comprised of analog, digital, and in some cases RF circuitry. Additionally, advanced thermal management systems, miniaturized connectors, and printed wiring board technologies would be needed to implement this subsystem technology.		
Dependencies: C22		

Spaceflight Instrumentation Technologies

Spaceflight instrumentation refers to the sensors and systems used to measure environments or behaviors of spaceflight systems, subsystems, or components. An instrumentation system is composed of multiple distributed elements, modules, or components that function together to process sensor measurements. A sensor is generally a single device used for making measurements, or a highly miniature set of components able to make 'smart' measurements. A 'smart' measurement results from the basic sensor reading being manipulated (e.g., adjusting the reading based upon a calibration curve or taking multiple measurements and synthesizing them into a single data point). Smart sensors also need to be adaptable to their environment and include self-test, self-calibration and self-diagnosis capabilities.

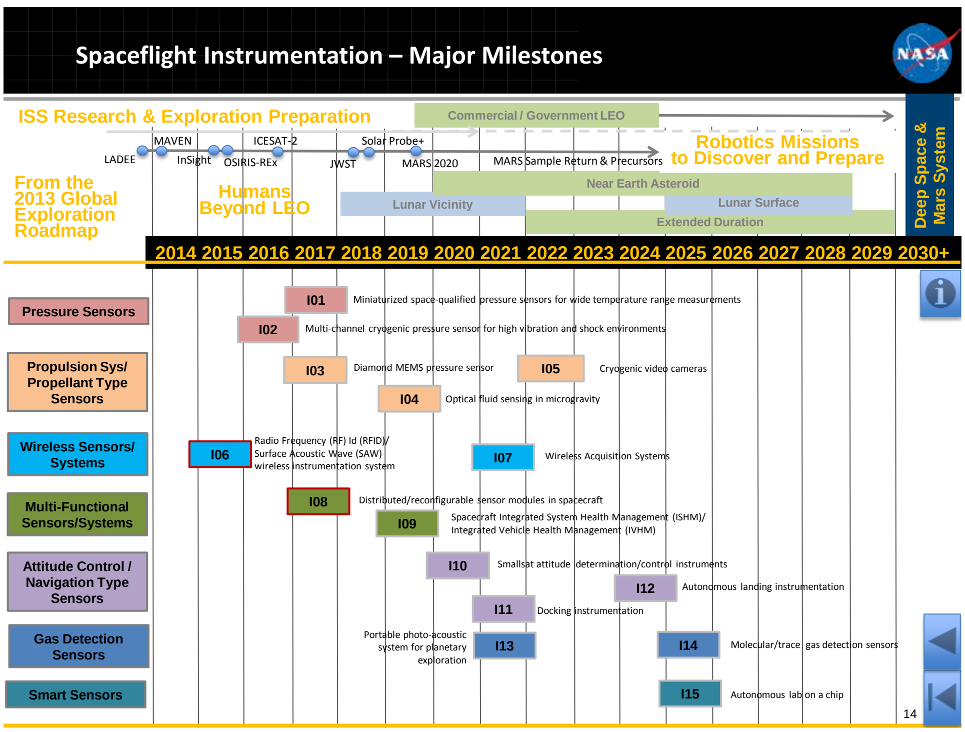

Figure 5. Spaceflight Instrumentation – Major Milestones

Pressure Sensors

I01: Miniaturized space-qualified pressure sensors for wide temperature range measurements		
Priority: **High**	*Target Date:* **2017**	*Benefit:* Sensors increase system reliability over a range of harsh conditions.
Description: Silicon-On-Insulator MicroElectroMechanical Systems (MEMS) pressure sensors are highly radiation tolerant and can measure real-time pressure at high temperatures and in harsh environments. Transducers can be packaged for a wide range of temperature (-250F to +350F).		
***Dependencies*: F14**		

I02: Multi-channel cryogenic pressure sensor for high vibration and shock environments		
Priority: **High**	*Target Date:* **2016**	*Benefit:* Sensors increase system reliability over a wide range of conditions.
Description: Designs using miniature piezo-resistive silicon pressure sensors to measure cryogenic fluid pressure accurately to within 0.25-percent full scale should be developed. Applications include launch vehicle cryo fuel tanks and engines, cryogenic wind-tunnels, industrial cooling, and cryogenic gas production.		
***Dependencies*: None**		

Propulsion Systems / Propellant Type Sensors

I03: Diamond MEMS pressure sensor		
Priority: **High**	*Target Date:* **2017**	*Benefit:* The Diamond MEMS pressure sensor provides simpler measurement approaches in extreme environments. The improved measurement accuracy leads to reduced margin requirements, and eliminates the need for redundant sensors on longer duration missions.
Description: Diamond MEMS pressure sensors are designed for extreme environments due to diamond's high elastic modulus and inertness. Current approaches to hydrazine measurements require isolation of the pressure sensor from the hydrazine environment, reducing accuracy of the measurement and producing a potential failure point. These failure points are realized regularly on longer duration missions and often require additional sensors be flown as a back-up.		
***Dependencies*: None**		

I04: Optical fluid sensing in microgravity		
Priority: **Medium**	*Target Date:* **2019**	*Benefit:* Optical based sensor designs are chemically/thermally passive to their environment and immune to electromagnetic interference.
Description: Development of optical based sensor designs using laser excitation and interferometry techniques to determine fluid depth or flow or fluid volume when dominated by the forces of surface tension and viscosity rather than gravity. Applications include measuring fluid supply line flow rates and storage tank fluid volumes in a microgravity environment.		
***Dependencies*: None**		

I05: Development of cryogenic video cameras		
Priority: **Medium**	*Target Date:* **2022**	*Benefit:* Being able to accurately gauge propellant tanks in low-gravity by the spacecraft or by mission control increases the chances for a successful mission.
Description: Developments in sensing of cryopropellants in microgravity and under impulse are needed for in-space propulsion systems for characterization of liquid level, slosh, and flow. Currently, video imaging is done through conventional cameras looking through windows which can present fracture problems. Alternative approaches to immerse the imager into the fluids present problems of both thermal control and assurance that the imager hardware does not contaminate the fluids.		
***Dependencies*: None**		

Wireless Sensors / Systems

I06: Radio Frequency (RF) Identification (RFID)/Surface Acoustic Wave (SAW) wireless instrumentation system		
Priority: **High**	*Target Date:* **2015**	*Benefit:* Potential weight reduction of the spacecraft cabling infrastructure, increase reliability and accessibility of sensors.
Description: Technology based on SAW development at the device level and with the interrogator RF system should be developed. A SAW-based instrumentation system helps to reduce instrumentation design complexity and avionics mass while reducing power requirements through passive sensing. Potential SAW based applications include low level hydrogen gas sensing for leak detection, liquid level and humidity sensing, and monitoring strain and pressure measurements.		
***Dependencies*: CT14**		

I07: Wireless Acquisition Systems		
Priority: **Medium**	*Target Date:* **2021**	*Benefit:* Standardization of wireless communication formats will help simplify solutions for integrated data acquisition systems.
Description: Development of wireless data acquisition systems which can integrate with each other is a desired technology. Various wireless acquisition systems exist in industry, but they use proprietary communication formats which makes integration difficult. A communication standard for sharing telemetry can allow partial wireless solutions to integrate with traditional wired acquisition system solutions.		
***Dependencies*: CT01, CT03, CT04**		

Multi-Functional Sensors / Systems

I08: Distributed/reconfigurable sensor modules in spacecraft		
Priority: **Medium**	*Target Date:* **2017**	*Benefit:* Reduce weight and increase reliability of avionics systems by using generic sensor modules, while lowering non-recurring engineering development costs. Simplify spacecraft avionics data acquisition with modules that can sense and record data from a variety of sensors.
Description: Developments in reconfigurable distributed avionics architecture can be based upon a small number of multi-purpose modules that can be individually changed to drive and sense a variety of mechanical and electrical components, characterized generally as either a multi-purpose electronic drive module or a multi-functional signal-conditioning module. The generic drive module can be configured to drive and control a variety of spacecraft avionics components: valves, motors, solenoids, pin pullers, thermostats, and heaters. A generic sensor module will be able to sense and record data from a variety of spacecraft avionics sensors: thermocouples, resistive temperature devices, potentiometers, encoders, tachometers, accelerometers, gyroscopes, and level and pressure sensors.		
***Dependencies*: F04, F05, F06, F11, F12, I06, CT14**		

I09: Spacecraft Integrated System Health Management (ISHM)/Integrated Vehicle Health Management (IVHM)		
Priority: **Medium**	*Target Date:* **2019**	*Benefit:* Increase reliability and operation of spacecraft systems.
Description: Development of reliable, believable (i.e., no false-positives) sensing devices to enable the ISHM/IVHM type of implementations is needed. ISHM systems include: sensors, anomaly detection, diagnosis, prognostics, user interfaces to provide integrated awareness of system condition, and new systems engineering processes enabled by intelligent elements that are part of the ISHM knowledge architecture.		
***Dependencies*: CD03, CD05, I06, I08, CT14**		

Attitude Control / Navigation Type Sensors

I10: Smallsat attitude determination/control instruments		
Priority: **Medium**	*Target Date:* **2020**	*Benefit:* Volume and mass reduction of spacecraft avionics especially for small satellites.
Description: Development of inexpensive attitude determination/control instruments for small satellites (e.g., nanosat or cubesat) is desired. These instruments must be designed to use low power and small volume and provide high precision to increase pointing accuracy.		
***Dependencies*: F06, F14, CD02, CD03, CD04**		

I11: Docking and close proximity operations instrumentation		
Priority: **High**	*Target Date:* **2021**	*Benefit:* Increase rendezvous/docking accuracy will help insure the safe operation of the spacecraft(s).
Description: Instruments and associated processing systems that enable safe real-time navigation and maneuvering in close proximity to small bodies, e.g., comets and asteroids as well as small moons and other primitive, low mass (low gravity) objects are desired. Used for autonomous robotic, teleoperated robotic, and crewed missions, these instruments are enabling for future solar system exploration and science missions. Examples include Doppler lidar velocimeters, flash lidar, and radar mapping systems.		
***Dependencies*: C01, C05**		

I12: Autonomous landing instrumentation		
Priority: **Medium**	*Target Date:* **2024**	*Benefit:* Increase landing accuracy will help insure the safe operation of the spacecraft.
Description: Development of precision landing and hazard avoidance instrumentation for autonomous landings is needed including instruments and associated processing systems for high-precision vehicle velocity vector determination, and altitude and attitude determination. Examples include Doppler lidar velocimeters, flash lidar, and radar mapping systems.		
***Dependencies*: C01, C05**		

Gas Detection Sensors

I13: Portable photo-acoustic system for planetary exploration		
Priority: **Medium**	*Target Date:* **2021**	*Benefit:* Very high sensitivity can be achieved. Instruments are extremely stable using microphones with a drift of <10% in 100 years.
Description: Photo-acoustic systems are designed to detect specific molecular species with high sensitivity (up to parts per trillion), using an array of microphones and array of infrared/ultraviolet light-emitting diodes to determine exact location and quantity of gaseous species of interest.		
***Dependencies*: F14**		

I14: Molecular detection/trace gas detection sensors		
Priority: **Medium**	*Target Date:* **2025**	*Benefit:* Highly sensitive gas detection.
Description: Development of intelligent, autonomous, distributed sensors (wired and wireless) for highly sensitive gas detection is desired. The sensors are based on nanostructures that can potentially respond to a single molecule. Dependent on RFID technology development.		
***Dependencies*: I06**		

Smart Sensors

I15: Autonomous lab on a chip		
Priority: **Medium**	*Target Date:* **2025**	*Benefit:* Increase reliability and weight reduction of spacecraft instrumentation systems.
Description: Development of miniature autonomous instrument sensors using 'smart' materials (i.e., materials with properties that can change in a controlled fashion by external stimuli) is desired. These instrument sensors have built-in capabilities to support sampling, sensor cleaning, and waste rejection schemes.		
***Dependencies*: C15**		

Communication and Tracking Technologies

The Communication and Tracking System provides the links to the spacecraft for command, telemetry and science data transfers as well as navigation support. Parts of the communication and tracking system include (but are not limited to) baseband processors, crypto devices, transponders/transceivers, optical terminals, antenna, filters, etc. Growing capabilities of science instruments, high quality imagery, and advanced mission concepts call for higher data rates, and networked communication at lower mass and power. To support these capabilities for future exploration systems, advances in communication technologies in the areas of internetworking, delay/disruption tolerant networking, location aware positioning, optical communication, communications security, etc. are needed. Communications should not be a limiting factor for a future mission.

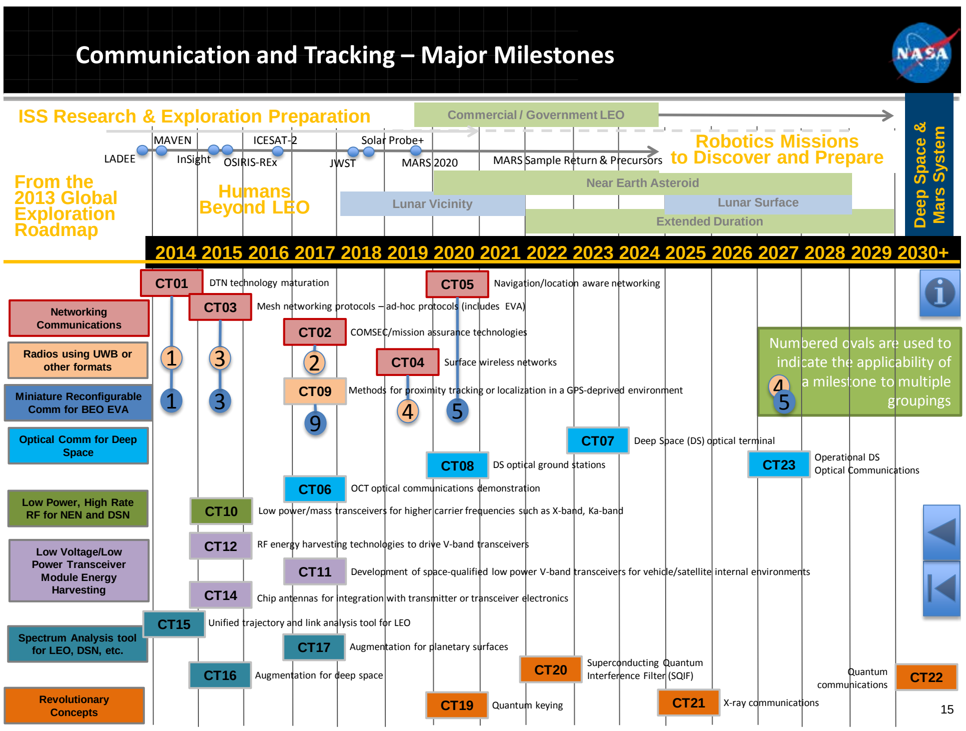

Figure 6. Communication and Tracking – Major Milestones

Networking Communications

<table>
<tr><td colspan="3">CT01: Disruption/Delay Tolerant Networking (DTN) technology maturation and validation using multi-center, International Partner and potentially International Space Station (ISS).
CT02: Communications Security (COMSEC)/mission assurance technologies for networked space communications
CT03: Mesh networking protocols – ad-hoc protocols (includes EVA applications for in-space and surface communications)
CT04: Surface wireless networks
CT05: Navigation/location aware networking</td></tr>
<tr><td>Priority:
High, High, High, High, High</td><td>Target Date:
2014, 2017, 2015, 2019, 2020</td><td>Benefit: Validated end-to-end architecture and standards for exploration internetworked, secure communications between multiple users /user classes.</td></tr>
<tr><td colspan="3">Description: Current space communication scenarios, for the most part, have involved fundamental point-to-point links between a spacecraft and Earth. Today's specialized link-layer protocols and carefully planned and scheduled link operations have thus far been adequate to meet the needs of missions. However, with a more networked communications architecture that is envisioned for deep space exploration and planetary surface operations, existing protocols and methodologies will need to evolve. Internetworking protocols that handle long link propagation delays and outages, and support surface wireless and proximity, quality of service, network management and information assurance, ad-hoc networking, etc., are critical in providing reliable, end-to-end communications. The above foundational technologies provide the necessary framework for networked communications for deep space exploration.</td></tr>
<tr><td colspan="3">Dependencies: CT02 - CT01, CT03; CT03 - CT01; CT04 - CT01, CT02, CT03; CT05 - CT01, CT02, CT03, CT09</td></tr>
</table>

Radios using Ultra-Wide Band (UWB) or other formats

CT01: DTN **CT02: COMSEC** **CT03: Mesh networking protocols – ad-hoc protocols (includes EVA applications for in-space and surface communications)** **CT04: Surface wireless networks** **CT09: Methods for proximity tracking or localization in a GPS-deprived environment**		
Priority: **High, High, High, High, Medium**	*Target Date:* **2014, 2017, 2015, 2019, 2017**	*Benefit:* Small scale solution, suitable for EVA and/or free-flyer/rover communications and tracking.
Description: A next generation, miniature, reconfigurable radio is called for to support the mass, volume, and power constraints of deep space exploration suits (2018-2020), wireless sensor networks, etc. It should incorporate DTN, mesh networking, surface wireless networks, navigation/location aware networking, wearable antenna, etc., to provide a system capable of supporting in-space EVA, surface EVA/robotic missions, and free flyers.		
***Dependencies*: CT02 - CT01, CT03; CT03 - CT01; CT04 - CT01, CT02, CT03**		

Miniature Reconfigurable Communications for Beyond Earth Orbit (BEO) EVA

CT01: DTN **CT03: Mesh networking protocols – ad-hoc protocols (includes EVA applications for in-space and surface communications)** **CT05: Surface wireless networks** **CT09: Methods for proximity tracking or localization in a Global Positioning System (GPS)-deprived environment**		
Priority: **High, High, High, Medium**	*Target Date:* **2014, 2015, 2020, 2017**	*Benefit:* Small scale solution, suitable for EVA and/or free-flyer/rover communications and tracking.
Description: Methods for proximity tracking or localization are required for both robotic and human surface- and space-based operations. In some cases, proximity tracking is required to supplement global tracking by providing greater accuracy relative to local landmarks. In other cases, proximity tracking is required during outages or gaps in a global tracking service. Examples include a robotic element or rover finding its way back to a base or intra-habitat navigation by a free-flyer within ISS or a deep space habitat.		
***Dependencies*: : CT03 – CT01; CT05 - CT01, CT02, CT03**		

Optical Communications for Deep Space

<table>
<tr><td colspan="3">CT06: OCT optical communications demonstration
CT07: Deep Space (DS) optical terminal
CT08: DS optical ground stations
CT23: Operational DS Optical Communications and Navigation</td></tr>
<tr><td>Priority:
Medium,
Medium,
Medium,
Medium</td><td>Target Date:
2017,
2023,
2020, 2027</td><td>Benefit: High Rate Communications from Deep Space at significantly lower power (and mass).</td></tr>
<tr><td colspan="3">Description: NASA is currently migrating to Ka-band for high-rate communications. However, it is anticipated that the demand for higher data rates will exceed the capacity available in the Ka-band spectrum given the mass and power constraints. At this stage, optical communications provide access to unregulated spectrum and will support the data rates needed by the next generation instruments, sensors, etc. Main challenges for deep space are the atmospheric issues and accurate acquisition and tracking of the target. These advances will be made with OCT TDM and other developmental test objectives.</td></tr>
<tr><td colspan="3">Dependencies: CT08 - CT06; CT07 - CT06, CT08; CT23 - CT07, CT08</td></tr>
</table>

Low Power, High Rate RF for Near Earth Network (NEN) and Deep Space Network (DSN)

<table>
<tr><td colspan="3">CT10: Low power/mass transceivers for higher carrier frequencies such as X-band, Ka-band</td></tr>
<tr><td>Priority:
Medium</td><td>Target Date:
2015</td><td>Benefit: Intermediate RF solution for High rate communication until Optical Comm comes on-board.</td></tr>
<tr><td colspan="3">Description: To bridge the gap to optical communications from deep space as well as to provide high-rate communications between exploration vehicles (space–to-space or space-to-surface), a low-power, high-rate Ka-band system with higher order modulation, coding, etc. reducing the mass and power required is needed. Mass and power reductions come with coding, miniaturization, advanced semiconductor technology, etc.</td></tr>
<tr><td colspan="3">Dependencies: None</td></tr>
</table>

Low Voltage / Low Power Transceiver Module Energy Harvesting

CT11: Development of space-qualified low power V-band transceivers for vehicle/satellite internal environments **CT12: RF energy harvesting technologies to drive V-band transceivers** **CT14: Chip antennas for integration with transmitter or transceiver electronics**		
Priority: **Medium, Medium, Medium**	*Target Date:* **2017, 2015, 2015**	*Benefit:* Provides backbone for high rate, ultra-low-power wireless sensors and instrumentation significantly reducing mass and power
Description: V-band could be beneficial for space-to-space (vacuum environment) at very high data rate links. Either vehicle to vehicle, or long haul. Hardware technology would include space qualified antennas, transceivers, and power amplifiers. V-band could also be used internal to the space vehicle for sensor data transfer/high data rate devices such as High Definition (HD) video, displays, laptops, and biomedical hardware. Sensors with integrated transmitters such as a thermocouple with transmitter all run off of parasitic energy sources. V-band could be used internal to the space vehicle for sensor data transfer/high data rate devices such as HD video, displays, laptops and biomedical hardware.		
***Dependencies*: CT11 - CT12, CT14**		

Spectrum Analysis Tool for Low Earth Orbit (LEO), Deep Space Network (DSN), etc.

CT15: Unified trajectory and link analysis tool for LEO **CT16: Augmentation for deep space** **CT17: Augmentation for planetary surfaces**		
Priority: **Low, Low, Low**	*Target Date:* **2014, 2015, 2017**	*Benefit:* A unified link analysis tool for different exploration destinations
Description: A spectrum analysis tool is needed that will assist designers in predicting communications performance for LEO, Lunar Surface Operations, and deep space applications that is aimed at providing analysis support as well as assistance in preparing data for spectrum applications. This tool could be seen as a product that calls a commercial product such as Satellite Tool Kit for underlying computations for orbits and access. It would also provide supplementary computations needed for the analysis, such as DSN interference estimates, planetary/Lunar surface multipath degradation effects, ITU surface power constraint estimates, etc.		
***Dependencies*: CT16 - CT15; CT17 - CT15, CT16**		

C&T Revolutionary Concepts

<table>
<tr><td colspan="3">CT19: Quantum keying
CT20: Superconducting Quantum Interference Filter (SQIF)
CT21: X-ray communications
CT22: Quantum communications</td></tr>
<tr><td>Priority:
Low,
Low,
Low,
Low</td><td>Target Date:
2020,
2022,
2025,
2030</td><td>Benefit: SQIF technology will provide huge performance improvements in terms of SWaP using detection of magnetic fields instead of electric fields.</td></tr>
<tr><td colspan="3">Description: From OCT – TA05: Advancement of X-ray navigation using X-ray emitting pulsars could provide the ability to autonomously determine position anywhere in the solar system just as GPS does for Earth inhabitants. Successful development of SQIF technology would change the paradigm for RF communication to detecting the magnetic field instead of the electric field and provide magnitudes of improvement in our communication systems.</td></tr>
<tr><td colspan="3">Dependencies: CT20 - CT19; CT22 - CT19, CT20</td></tr>
</table>

Human Interface Technologies

Computer-Human Interface is an interdisciplinary field which is focused on the interaction between human users and computer systems including the user interface and the underlying processes which produce the interactions. From the human perspective, interaction with the world around us is achieved through our five senses: hearing (auditory interfaces), touch (tactile interfaces), sight (visual interfaces), smell (olfactory interfaces) and taste (gustation interfaces). Olfactory and gustation interfaces have not been included in this roadmap because they are extremely immature technologies and it is unclear which discipline area will implement these types of interfaces (electrical, chemical, etc.).

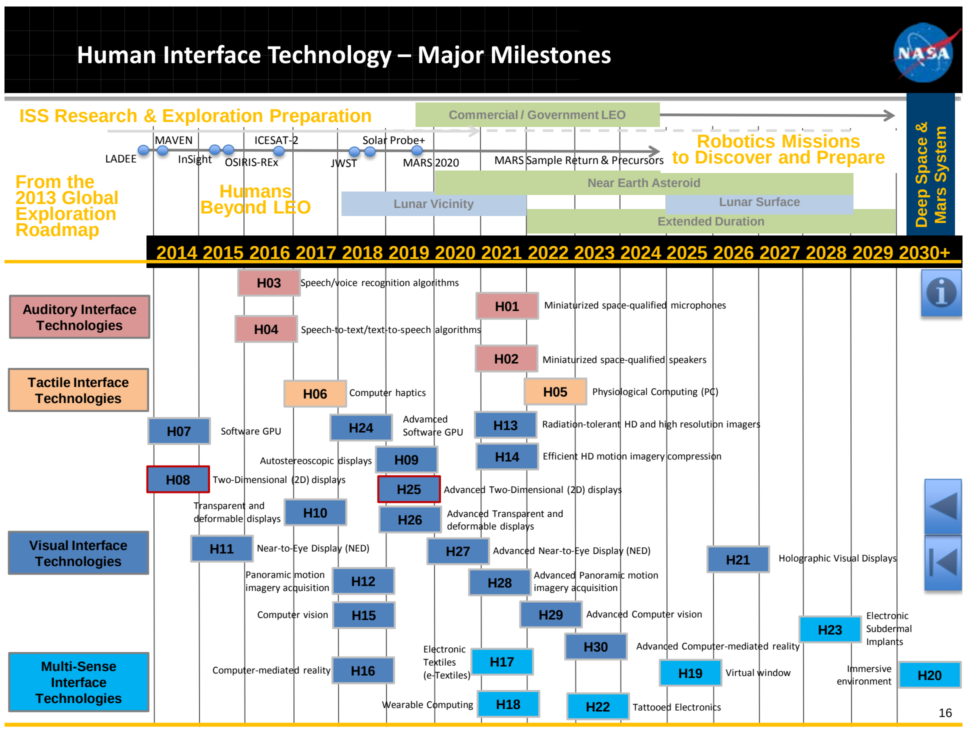

Figure 7. Human Interfaces – Major Milestones

Auditory Interfaces

H01: Miniaturized space-qualified microphones **H02: Miniaturized space-qualified speakers**		
Priority: **MEDIUM**	*Target Date:* **2021**	*Benefit:* **Miniaturization of speakers and microphones for spaceflight will decrease the size, weight and power requirements for audio interfaces and enable wearable applications beyond traditional ear-attached devices.**
Description: Several technologies are under development which will miniaturize microphones and speakers and allow applications in new contexts. For example, development of distributed planar array microphones, coupled with Micro-Electro-Mechanical Systems (MEMS) technology, will facilitate ubiquitous voice communications without use of crew-worn or hand-held microphones. Also, customization of commercial bone conduction technology for use with traditional dynamic and electret microphones will improve voice communications and speech recognition. As for speakers, implementation of edge vibrated, electrostatic and distributed mode technology will produce low mass, low power, and space efficient loud speakers. Due to the advancement in commercial products, investment by NASA in these areas should not be in advancing the technology itself, but instead in adapting this technology to the unique environmental challenges of human spaceflight.		
***Dependencies*: F16**		

H03: Speech/voice recognition algorithms **H04: Speech-to-text/text-to-speech algorithms**		
Priority: **LOW**	*Target Date:* **2016**	*Benefit:* **Accurate speech/voice recognition and speech-to-text/text-to-speech algorithms will be imperative for space-to-ground communications on high latency links.**
Description: Development of accurate speech recognition technology capable of adapting to physiological effects of spaceflight on the human vocal tract is required. This area includes development of a redundant speech recognizer for reliable voice control of systems. Commercial advancements in recent years in speech/voice recognition algorithms make investment by NASA in this area a low priority. Where NASA investment would be beneficial is in adaptation of these algorithms for specific human spaceflight issues such as noisy environments like ISS, heavy use of systems by both native and non-native English speakers, compensating for physiological and psychological factors affecting the speech process. Adaptation of these algorithms to handle the heavy use of NASA specific lingo and acronyms and development of a redundancy scheme that allows for reliable voice control of critical flight systems. Additionally, optimization of speech-to-text/text-to-speech technology is required to support low data rate/high latency communication links. This technology will improve space-to-ground communications on high latency links by providing textual conversion of dialog and can be used for real-time dictation in flight. This will include computer speech with good intelligibility.		
***Dependencies*: None**		

Tactile Interfaces

H05: Physiological Computing (PC)		
Priority: **LOW**	*Target Date:* **2022**	*Benefit:* **Physiological Computing could have a dramatic impact on decreasing crew workload and increasing crew accuracy.**
Description: PC is a term used to describe any computing system which uses real-time physiological data as an input stream to control the user interface. The most basic PC is one which records a signal such as heart rate and displays it to the viewer via a screen. Other systems, such as brain-computer interfaces or unvoiced speech recognition, take a stream of physiological data (electrical activity from the brain or muscles) and convert it into input control at the interface, e.g., to move a cursor or select a command. Other types of PC simply monitor physiology in order to assess psychological states and trigger real-time adaptation. For example, if the system detects high blood pressure, it may assume the user is experiencing high frustration and offer help. The applications for PC range from adaptive automation in an aircraft cockpit to computer games where electrical activity is used to initiate particular commands. Most advanced PC applications (such as brain-computer interfaces) are in the low TRL stages and heavy investment by NASA is not currently recommended.		
***Dependencies*: C17, I07**		

H06: Computer haptics		
Priority: **LOW**	*Target Date:* **2017**	*Benefit:* **Computer haptic will have a significant impact on wearable/hands-free operation, as well as realism in immersive environments which will bring the experience of spaceflight to Earth and experiences from Earth to the crew.**
Description: Haptics is a highly interdisciplinary technology area which aims to define how humans and machines touch, explore, and manipulate objects in real, virtual, or teleoperated worlds. Haptics have been used to allow teleoperators to feel what a robot touches and to increase realism in training applications. Flight simulators equipped with force feedback joysticks provide a convincing example for the importance of simulation technology and the significant role haptics play in training. Several studies in the past have shown the significance of haptics in teleoperation tasks in real and virtual worlds. For example, artificial force fields not only enable us to train the human operator in virtual environments, but also help him or her execute the teleoperated task better and faster in the real world. Significant progress has been made in haptics, but there are still many research questions waiting to be answered. One of the constant challenges in integrating haptics into virtual environments is the need for a variety of haptic devices with the requisite degrees of freedom, range, resolution, and frequency bandwidth, both in terms of forces and displacements. Another area of hardware design which requires further investigation is multi-fingered haptic devices and tactile displays. It has been demonstrated, as we gather information about the shape and size of an object through touch, our fingers and hand move in an optimal manner. Moreover, robotics studies show at least three fingers are necessary for stable grasp. On the other hand, there are only a few multi-fingered haptic devices which are commercially available today.		
***Dependencies*: None**		

Visual Interfaces

<table>
<tr><td colspan="3">H07: Software Graphics Processing Unit (GPU)
H24: Advanced Software GPU</td></tr>
<tr><td>Priority:
HIGH</td><td>Target Date:
2014, 2018</td><td>Benefit: Visual displays are the primary interface between the crew and spacecraft data, and this is not expected to change in the near term. There are currently no known GPU solutions that will reliably function in a deep space environment.</td></tr>
<tr><td colspan="3">Description: GPUs are very efficient processors that manipulate computer graphics. Their highly parallel structure makes them more effective than general-purpose CPUs for algorithms where processing of large blocks of data is done in parallel. Commercial GPUs have not been shown to be adequate for high-reliability applications within the radiation environment of spaceflight (i.e. dynamic flight phases and high criticality applications). The solution used for the Space Shuttle severely limited the capabilities of the graphics and drastically trails the capabilities of commercial GPUs used on Earth. For long-duration missions, with increasing requirements for information access, it will be critical to increase the ability of space qualified GPUs. One promising technology for creating a radiation tolerant GPU is to implement the capability within a general-purpose CPU.</td></tr>
<tr><td colspan="3">Dependencies: H07 – None; H24 - C01, C02, C03, C04</td></tr>
</table>

<table>
<tr><td colspan="3">H08: Two-Dimensional (2D) displays
H25: Advanced 2D displays</td></tr>
<tr><td>Priority:
HIGH</td><td>Target Date:
2014, 2019</td><td>Benefit: 2D visual displays are primary interface between the crew and spacecraft data, and this is not expected to change in the near term. Adaption of newer technologies is imperative to decrease the size, weight and power consumption of traditionally large, heavy, high power display units.</td></tr>
<tr><td colspan="3">Description: Traditional 2D displays are constantly evolving. The next generation of these visual displays appears to be Organic Light-Emitting Diode (OLED) technology which significantly reduces size, weight, and power requirements for visual displays. Also, depending on the application, e-Ink displays could have similar benefits. However, other technologies are emerging which could have impact beyond OLED, such as quantum dot, bistable, and laser-phosphor displays. While the commercial industry is far ahead of NASA in display development technology, where NASA should invest their limited resources is in early space flight environmental testing of different display types. With good environmental data NASA may be able to influence commercial development display manufacturing lines as each display type evolves.</td></tr>
<tr><td colspan="3">Dependencies: H08 – H07; H25 – C13</td></tr>
</table>

H09: Autostereoscopic displays		
Priority: **LOW**	*Target Date:* **2019**	*Benefit:* **Utilization of autostereoscopic displays in spacecraft will increase immersion and open up new information display possibilities allowing for quicker information access and management of extremely large data sets.**
Description: Autostereoscopic displays are able to provide binocular depth perception without the hindrance of specialized headgear or filter/shutter glasses. At its simplest, this is 3-D television (3DTV). However, the technology is also progressing toward digital holographic prints and video. Some of the various technologies which are competing to best implement an autostereoscopic display are parallax barrier, lenticular, volumetric, electro-holographic, and light field displays.		
***Dependencies*: C13, H07**		

H10: Transparent and deformable displays **H26: Advanced transparent and deformable displays**		
Priority: **MEDIUM**	*Target Date:* **2017, 2019**	*Benefit:* **Transparent and deformable displays will revolutionize EVA activities, allowing for higher efficiency and accuracy. These technologies will also drastically increase efficiency of crew maintenance activities both IVA and EVA.**
Description: Additional layers of capability which are being added to display technologies are transparency and deformation. These capabilities lead toward development of more useable near-to-eye displays, as well as new ways to unobtrusively integrate displays into the environment. These capabilities are being explored through traditional 2D-type displays, as well as through projection and printable displays.		
***Dependencies*: H10 – H07; H26 – C13**		

H11: Near-to-Eye Display (NED) **H27: Advanced NED**		
Priority: **MEDIUM**	*Target Date:* **2015, 2020**	*Benefit:* **Near-to-Eye Displays are essential in moving toward truly wearable/mobile crew operations, allowing for frictionless interaction between crew and the spacecraft. This technology will have significant impacts on EVA operations to allow the crew access to visual information that they have as of yet been unable to see.**
Description: NEDs have been classified into one of three categories based on the mode of image presentation. Monocular NEDs usually have only one display; in binocular (stereo) NEDs, two disparate images are presented on two displays; in bi-ocular mode the same image is presented on two displays. Different types of NED are beneficial for different applications. Two of the most impactful applications of NEDs are virtual reality (presenting an entirely virtual world to the user) and augmented reality (presenting digital information onto the real world).		
***Dependencies*: H11 – H07; H27 – C13, CT04**		

H12: Panoramic motion imagery acquisition **H28: Advanced panoramic imagery acquisition**		
Priority: **LOW**	*Target Date:* **2018, 2021**	*Benefit:* **Panoramic motion imagery acquisition is required for displaying an immersive environment of real-time video.**
Description: Panoramic image acquisition is based on mosaic approaches developed in the context of still imagery. Mosaics are created from multiple overlapping sub-images pieced together to form a high-resolution, panoramic or wide field-of-view image. While still imagery mosaics and panoramas are common, high-resolution real-time panoramic video is an emerging area. For panoramic, real-time High Definition (HD) video, an array of video cameras view the scene, while a digital recording and playback system maintains precise frame synchronization, allowing the frames to be stitched together. The challenges encountered in this process span issues in camera calibration, real time scene stitching, image processing, compression, networking, computer graphics, and high-performance computing.		
***Dependencies*: H12 - C01, C04, C10; H28 - C15, H13, H14**		

H13: Radiation-tolerant HD and high resolution imagers		
Priority: **HIGH**	*Target Date:* **2017**	*Benefit:* **Radiation-tolerant HD and high resolution imagers are critical for video needed for safety-critical mission inspection operations.**
Description: The image sensors used for spaceflight applications have historically been commercially available sensors which are vetted through radiation testing on the ground and flown for a limited lifetime until they degrade to a predetermined limit. Then, they are discarded and replaced. For long-duration missions beyond LEO, radiation-tolerant high-definition video and high resolution still imagers will be required. Unfortunately no other industry is heavily vested in this particular technology area, so it will be imperative for NASA to invest in and develop the technology needed in this area.		
***Dependencies*: C15**		

H14: Efficient HD motion imagery compression		
Priority: **HIGH**	*Target Date:* **2020**	*Benefit:* **Efficient HD motion imagery compression is critical for bringing video back to Earth in order to perform safety-critical mission inspection operations.**
Description: Motion imagery compression reduces the amount of data used to represent digital video images, and combines spatial image compression and temporal motion compensation. Most video compression is inadequate; it operates on the premise much of the data present before compression is not necessary for achieving good perceptual quality. Some forms of data compression are lossless. This means the data is decompressed, resulting in a bit-for-bit perfect match with the original. While lossless compression of video is possible, it is rarely used, since traditional compression results in far higher compression ratios at an acceptable level of quality. However, in spaceflight applications where very few or no humans are present, video is the primary method we have to experience the mission environment. Future NASA missions will require higher compression ratios without sacrificing image quality.		
***Dependencies*: C01, C04, C10, C15**		

H15: Computer vision **H29: Advanced computer vision**		
Priority: **MEDIUM**	*Target Date:* **2018, 2022**	*Benefit:* **Computer vision will decrease the time impact and increase the accuracy of maintenance activities aboard a spacecraft. Additionally, computer vision will unburden much of our currently “manual” image analysis for safety-critical inspection capability.**
Description: Computer vision is the field concerned with the automated processing of images from the real world to extract and interpret information on a real-time basis. It is the science and technology of machines which see. Here, “see” means the machine is able to extract information from an image, to solve some task, or perhaps understand the scene in either a broad or limited sense. The field includes scene reconstruction, event detection, and video tracking (3D human body tracking, including eye/gaze tracking, object recognition, learning, indexing, motion estimation and image restoration).		
***Dependencies*: H15 - C01, C04, C10; H29 - H12, H13, H14**		

H16: Computer-mediated reality **H30: Advanced computer mediated reality**		
Priority: **MEDIUM**	*Target Date:* **2018, 2023**	*Benefit:* **Computer-mediated reality will increase situational awareness of crew members by immediately providing vehicle health and status information, along with caution and warning alerts in a mobile or wearable computing platform. Additionally, computer-mediated reality will decrease the time impact and increase the accuracy of maintenance activities aboard a spacecraft.**
Description: Computer-mediated reality refers to the ability to add or subtract information or otherwise manipulate one's perception of reality through the use of a wearable computer or hand-held device. Typically, it is the user's visual perception of the environment which is mediated. This is done through the use of some kind of electronic device which can act as a visual filter between the real world and what the user perceives. The field of computer-mediated reality encompasses augmented reality (adding or subtracting digital information to the real world) and virtual reality (immersion into a completely digital world).		
***Dependencies*: H16 - C01, C04, C10, H10, H11; H30 - H12, H13, H14, H15**		

H21: Holographic Visual Displays		
Priority: **LOW**	*Target Date:* **2026**	*Benefit:* **Holographic Visual Displays will take a user a huge step closer to a truly immersive environment then the current 2D and 3D visual displays. This technology could allow the user to interact with object and even people as if they are physically present.**
Description: A holographic display is basically a type of display technology that has the ability to provide all four eye mechanisms: binocular disparity, motion parallax, accommodation and convergence. It involves the use of a laser, interference, diffraction, light intensity recording and suitable illumination of the recording. The image changes as the position and orientation of the viewing system changes in exactly the same way as if the object were still present, thus making the image appearthree-dimensional.		
***Dependencies*: C13, H07**		

Multi-Sense Interfaces

H17: Electronic Textiles (e-Textiles) **H18: Wearable Computing**		
Priority: **LOW**	*Target Date:* **2021**	*Benefit:* **There are numerous potential benefits to e-Textiles and Wearable Computing, most notably are mobile, on-demand access to space vehicle and robotic displays and controls; multi-modal caution and warning using tactile, auditory and visual alarms; and wireless, hands-free, on-demand voice communication. All of this benefits will increase crew reaction time to critical safety situations.**

Description: E-textiles are fabrics which have electronics and interconnections woven into them offering physical flexibility and size which cannot be achieved with existing electronic manufacturing techniques. Components and interconnections are intrinsic to the fabric and thus are less visible and not susceptible to becoming tangled or snagged by the surroundings. An e-textile can be worn in everyday situations where currently available wearable computers would hinder the user. E-textiles can also more easily adapt to changes in the computational and sensing requirements of an application, a useful feature for power management and context awareness. For NASA, e-textiles show a great deal of promise in improving crew life and efficiency in a wide variety of ways including:

- Mobile, on-demand access to space vehicle and robotic displays and controls
- Multi-modal caution and warning using tactile, auditory, and visual alarms
- Wireless, hands-free, on-demand voice communication
- Continuous biomedical monitoring for research and detection of health problems
- Activity monitoring for responsive robotics and environments
- Environmental monitoring for individual exposure assessments and alarms

Many technical challenges must still be overcome by NASA to realize these wearable technology applications. For example, to make a comfortable garment, electronic components must be small, flexible, and lightweight. They must be placed in locations that are appropriately accessible but not intrusive, and integrated into the garment with advanced manufacturing techniques. Limited power is available from body-worn batteries and heat must be managed to prevent discomfort. If the clothing is to be washed, there is additional durability and wash-ability hurdles that traditional electronics are not designed to address. Finally, each specific capability has unique technical challenges that will likely require unique solutions.

Wearable computing is miniature devices that are worn by the user under, with or on top of clothing. Some of the most recent, notable applications in this field today are items like electronic glasses (e.g., Google Glasses), watches (e.g., Sony SmartWatch) and exercise aids/trackers (e.g. FuelBand, Fitbit, JawboneUp). These types of devices allow a user to create their own personal area network and will eventually provide a significant change in mobility and its uses. When wearable computing is combined with the e-textile field smart clothing will allow an astronaut to become more efficient and self-sufficient than ever before.

***Dependencies*: C14, C15, CD01, I07, I08, CT03, CT05**

H19: Virtual window		
Priority: **LOW**	*Target Date:* **2025**	*Benefit:* **Virtual windows will drastically reduce the structural concerns on including optical windows in a spacecraft and increase situational awareness and vehicle inspection capability.**
Description: A virtual window utilizes digital technology to simulate an optical window including the changes in perspective due to the movements of the observer. The ultimate implementation would include autostereoscopic video/displays, panoramic motion imagery acquisition, ambiance audio, pan/tilt/zoom for situational awareness, and radiation tolerant video and graphics. A virtual window is technology that could be used by NASA to save significant weight in the spacecraft structure. Spacecraft windows are heavy and are often one of the weakest points in the vehicle structure. In addition to weight savings, the ability to multipurpose this technology for other uses, such as acting as the vehicle's primary display system		
***Dependencies*: C01, C04, C10, H07, H13, H14**		

H20: Immersive environment		
Priority: **LOW**	*Target Date:* **2030**	*Benefit:* **Immersive environment technologies will provide crews of long duration missions a crucial psychological connection back to Earth. Immersive environments also allow those here on Earth a valuable look into life aboard a spacecraft and a valuable tool for real-time mission troubleshooting.**
Description: An immersive digital environment is an artificial, interactive, computer-created scene or world within which a user can immerse one's self. Immersive digital environments could be synonymous with virtual reality without the implication actual reality is being simulated. An immersive digital environment could be a model of reality but it could also be a complete fantasy user interface or abstraction as long as the user of the environment is immersed within it. The definition of immersion is wide and variable but here it is assumed to simply mean the user feels like he or she is part of the simulated universe. The success with which an immersive digital environment can actually immerse the user is dependent on many factors such as believable 3D computer graphics, surround sound, interactive user input, and other factors such as simplicity, functionality, and potential for enjoyment. To create a sense of full immersion, the five senses (sight, sound, touch, smell, taste) must perceive the digital environment to be physically real. Immersive technology can perceptually fool the senses through: • Panoramic 3D or holographic displays (visual) • Surround sound acoustics (auditory) • Haptic and force feedback (tactile) • Smell replication (olfactory) • Taste replication (gustation) Some potential applications for an immersive environment include crew recreation, training, and troubleshooting.		
***Dependencies*: C01, C04, C10, C13, H01, H02, H03, H05, H06, H07, H09, H11, H16, H18, H19**		

<table>
<tr><td colspan="3">H22: Tattooed Electronics</td></tr>
<tr><td>Priority:
LOW</td><td>Target Date:
2023</td><td>Benefit: Tattooed electronics will be a transitional technology between non-intrusive wearable technologies and subdermal implants. By printing the electronic mesh directly onto skin, the sensor becomes approximately 1/30 the size and even conforms better to that body's natural bumps and curves.</td></tr>
<tr><td colspan="3">Description: Tattooed electronics allow sensors and communications electronics to be worn on the skin as easily as a temporary tattoo. The electronics could include electrophysiological and physical sensors as well as wireless communication modules. Recordings for EEG, EKG/ECG, and EMG sensors (measuring electrical activity in the brain, heart,
and skeletal muscles respectively) could be comparable to data obtained via bulky commercial devices. Additionally, there are a myriad of other uses in human-machine interfaces. For example, when mounted to a user's throat, simple spoken commands can be translated into electrical controls.</td></tr>
<tr><td colspan="3">Dependencies: H05, H17, H18</td></tr>
</table>

Conclusion

The Avionics Technology Roadmap takes an 80% approach to technology investment in spacecraft avionics. It delineates a suite of technologies covering foundational, component, and subsystem-levels, which directly support 80% of future NASA space mission needs. The roadmap eschews high cost, limited utility technologies in favor of lower cost, and broadly applicable technologies with high return on investment. The roadmap is also phased to support future NASA mission needs and desires, with a view towards creating an optimized investment portfolio that matures specific, high impact technologies on a schedule that matches optimum insertion points of these technologies into NASA missions. The roadmap looks out over 15+ years and covers some 114 technologies, 58 of which are targeted for TRL6 within 5 years, with 23 additional technologies to be at TRL6 by 2020. Of that number, only a few are recommended for near term investment:

1. Rad Hard High Performance Computing
2. Extreme temperature capable electronics and packaging
3. RFID/SAW-based spacecraft sensors and instruments
4. Lightweight, low power 2D displays suitable for crewed missions
5. Radiation tolerant Graphics Processing Unit to drive crew displays
6. Distributed/reconfigurable, extreme temperature and radiation tolerant, spacecraft sensor controller and sensor modules
7. Spacecraft to spacecraft, long link data communication protocols
8. High performance and extreme temperature capable C&DH subsystem

In addition, the roadmap team recommends several other activities that it believes are necessary to advance avionics technology across NASA:

- Engage the OCT roadmap teams to coordinate avionics technology advances and infusion into these roadmaps and their mission set
- Charter a team to develop a set of use cases for future avionics capabilities in order to decouple this roadmap from specific missions
- Partner with the Software Steering Committee to coordinate computing hardware and software technology roadmaps and investment recommendations
- Continue monitoring foundational technologies upon which future avionics technologies will be dependent, e.g., RHBD and COTS semiconductor technologies

The ASC Technology Roadmap team would like to thank the ASC membership for the opportunity to develop this important strategic document, which it believes should be updated on a yearly to bi-yearly basis in order to keep up with this highly dynamic and rapidly advancing field.

Acronyms

2D	Two-Dimensional
3-D	Three-Dimensional
ASC	Avionics Steering Committee
ASIC	Application-Specific Integrated Circuit
C	Celsius
C&DH	Command and Data Handling
CMOS	Complementary Metal-Oxide Semiconductor
COMSEC	Communications Security
DARPA	Defense Advanced Research Projects Agency
DDR	Double Data Rate
DRM	Design Reference Mission
DS	Deep Space
DSN	Deep Space Network
DTN	Delay-Tolerant Network
DTRA	Defense Threat Reduction Agency
EVA	Extravehicular Activity
FeRAM	Ferroelectric Random-Access Memory
FPGA	Field Programmable Gate Array
GaN	Gallium Nitride
Gb/s	Gigabits Per Second
GPS	Global Positioning System
HD	High Definition
I/O	Input/Output
ISHM	Integrated System Health Management
ISS	International Space Station
IVHM	Integrated Vehicle Health Management
krad	Kilorad
LEO	Low Earth Orbit
Mb/s	Megabit Per Second
MEM	Microelectromechanical
MIT	Massachusetts Institute of Technology
MPCV	Multi-Purpose Crew Vehicle
MRAM	Magnetoresistive Random Access Memory
NEA	Near Earth Asteroid
NED	Near-to-Eye Display
nm	Nanometer
NRO	National Reconnaissance Office
OCT	Office of the Chief Technologist
OLED	Organic Light-Emitting Diode

phy	Physical
PC	Physiological Computing
PCRAM	Phase-Change Random-Access Memory
RAM	Random Access Memory
QML	Qualified Manufacturer List. – QML
RF	Radio Frequency
RFID	Radio Frequency Identification
RH	Radiation Hardened
RHBD	Radiation Hardening By Design
SAW	Surface Acoustic Wave
SBC	Single Board Computer
SDRAM	Synchronous Dynamic Random Access Memory
SiGe	Silicon-Germanium
SiC	Silicon Carbide
SIMD	Single Instruction Multiple Data
SLS	Space Launch System
SOC	System On Chip
SOI	Silicon-On-Insulator
SONOS	Silicon-Oxide-Nitride-Oxide Silicon
SQIF	Superconducting Quantum Interference Filter
SRAM	Static Random Access Memory
THz	Terahertz
TRL	Technology Readiness Level
TSV	Through Silicon Via
µm	Micrometer

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13. ABSTRACT *(Maximum 200 words)*
The results of the 2014 update of NASA's Avionics Steering Committee (ASC) Technology Roadmap are provided. This is the result of a multi-center effort directed by the ASC to address its stated goal "to advance the avionics discipline ahead of program and project needs". The NASA ASC is chartered out of the Office of Chief Engineer (OCE), and represents the Agency's avionics workforce through its line management representatives. The ASC Technology Roadmap is intended to strategically guide avionics technology development to effectively meet future NASA missions' needs. The roadmap addresses only flight avionics hardware and did not consider ground-based electronics, flight software, or ground software. The ASC Technology Roadmap looks out over 15+ years, with near-term focus on evolving technologies and a long-term look at technologies that are more revolutionary. From the key technologies identified, a subset was selected for near term Agency investments. Factors considered in making this selection included readiness of the technology itself, potential for external partners to help develop it, and existing/future NASA technology development investments. The ASC has also identified future efforts "to advance the avionics discipline ahead of program and project needs."

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