Surface Deformation and Change
Technology Survey

A report by the SDC Technology Steering Committee

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Further Information

Additional information about the Surface Deformation and Change mission architecture study including upcoming events and current progress can be found at the SDC website:

https://science.nasa.gov/earth-science/decadal-sdc

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Executive Summary

The surface deformation and change (SDC) observation requested by the National Academies Decadal Survey for Earth Science [1] released in 2018 is a designated observable (DO), the highest priority level defined. The SDC architecture study team is tasked with recommending a set of mission architectures that will deliver the best science value to NASA as it relates to the science objectives given in the decadal survey. The team has developed a five year plan to formulate this mission architecture tailored to NASA's desired profile, but this effort could be accelerated if needed.

Surface deformation measurements using repeat-pass synthetic aperture radar (SAR) interferometry were pioneered twenty years ago and have an established performance track record. The architecture study team assumes that this technology will make up the core of the SDC mission, although augmentation using other sensor technologies will be considered. The decadal survey emphasizes geodetic measurements based on the coherent phase of the radar images and explicitly serves the solid Earth, cryosphere, and hydrology science communities. NASA has also asked the study team to consider radiometric imagery and the ecosystems science community in the architecture trade space even though it is not explicitly requested in the decadal survey.

Repeat-pass interferometry works by taking two coherent radar images of a scene with identical viewing geometries separated by some amount of time. By differencing the phase of the two scenes, the residual product reveals any changes that occured within the scene over that time period. Many orbital SAR systems have some capability to make this measurement, but the NISAR mission, with a repeat time of 12 days and launching in 2021, will be the first instrument specifically designed to collect this measurement and get global background coverage for the purpose of interferometry. SDC seeks to build on this measurement and provide continuity after the NISAR mission is complete by achieving faster revisit times at sub-weekly repeat rates. Many natural processes need more frequent sampling than the twelve days NISAR will provide, still with the global coverage. Most needs center around 10 m resolution, with deformation accuracy of 1 mm/yr.

The architecture study team has taken a two-pronged approach to start the study in a way that maximizes community involvement with the process. This engagement has taken the form of workshops. The first workshop engaged stakeholders from NASA and academia to refine the science requirements that make the most sense for a future mission from the impacted science communities. The second workshop, and the focus of this report, engages NASA and industry on technology areas that might be brought to bear on this mission in order to reduce mass, power, volume, and ultimately cost. NASA has given a guideline for the SDC mission of $500M, a considerable challenge for orbital SAR missions with demanding operating requirements.

The technology workshop was held May 20th-22nd, 2019 at the Pasadena Convention Center. The event was staged simultaneously with, but separately from, the annual Space

Tech Exposition that also occurs at the convention center. The co-location of these events had the benefit for SDC of obtaining access to leading experts from a variety of technology fields who were already gathered nearby for a similar purpose but covering the entire aerospace industry. The workshop was organized into panel sessions over the first two days, where subject matter experts in a particular technology field would sit on the panel and address the SDC technology steering committee consisting of SDC leadership and other NASA technologists. Each panelist presented a quick overview of technologies in round robin fashion followed by question and answer sessions designed to probe the intersection between the technologies and SDC needs. The third day was used for the SDC team to digest the information heard over the preceding two days and to formulate the recommendations presented in this document. This document is therefore intended as a road map for our future technology efforts related to developing possible mission architectures.

Following the workshops, the SDC architecture team will start detailed architecture development through the use of several concurrent engineering centers at NASA. These studies will involve a small number of core participants from around NASA. In order to maintain broader community engagement through this process, the study teams will produce requests for information (RFI) to obtain more specifics on a certain technology and requests for proposals (RFP) in order to advance a technologies' readiness for use in the SDC environment. These requests will be announced through NASA's science mission directorate and also posted on the SDC website and broadcast via the RFI mailing lists available there: https://science.nasa.gov/earth-science/decadal-sdc

Session topics for the SDC technology workshop were selected based on the mission areas most impactful for an orbital SAR instrument. These areas extend beyond the space segment itself and includes the infrastructure needed to get the data to the end science and applications users. SAR instruments require a large aperture to make their measurements and the technologies to produce these antennas covered one session. These antennas then need to be accommodated on a spacecraft bus, which also provides power for the large transmitter, which comprised another session. The increased power dissipation, particularly when operating over a significant portion of the orbit as SDC needs to do, requires advanced thermal technologies to dissipate that heat and that also comprised a session. A related special topic on hyper-integration covered the design trend of trying to combine multiple functions into a single component in order to reduce mass and volume. Another session covered the on-board processing technologies used to process the data on orbit to reduce data rate to the ground. These sessions comprised the first day of discussions centered around technologies needed for the space segment of a SAR mission.

The second day covered the other mission systems that make up a SAR mission as well as external factors that might influence the design of the SDC mission in the current landscape. The sessions included telecom and ground stations to downlink the SAR data to the ground and get it to the cloud. Another session was on big data and analytics that covered how to handle the large volume of data accumulating over the mission lifetime and how that data is identified and distributed to the community at large. A session on commercial data covered the available SAR data from commercial enterprises that might be useful to NASA, and how that data might fit into NASA's open and free data policy. A similar session on radar instruments sought to explore how existing instruments might be adapted to SDC needs and any cost efficiencies associated with that. A session on observation strategies sought alternative viewing geometries that might offer unique measurement opportunities for SDC not considered in traditional architectures. Finally, a special topic on launch options from Kennedy Space Center covered the process for selecting a launch vehicle and how to properly engage KSC and estimate costs.

Details for each of these sessions can be found in their respective sections within this document. A summary of the outcomes from each session is listed in the following section.

Listing of Findings, Recommendations, and Actions

Thanks to the discussions and inputs at this technology workshop, the SDC team feels it has been able to identify several critical technologies for improving size, weight, and power (SWaP) on any candidate radar instrument, and this will in turn reduce overall mission costs. These technologies therefore receive our highest level of recommendation for development at this stage of our study. The implementation of these technologies may vary depending on the mission architecture chosen, but we expect to see improvements regardless of architecture. These technologies include RF System-on-Chip (SoC) FPGAs, which combine multiple analog-to-digital and digital-to-analog converters with programmable logic and processors on a single chip. Not only does this save physical area, by eliminating the high power IO circuitry it also offers significant power savings. Additive manufacturing is another technology that can impact any future architecture. Striving to minimize cable interfaces through the use of backplanes and standardized form factors minimizes volume and mass but degrades the ability to remove heat from the electronics. Additive manufacturing has the potential to offer solutions in this area through the formation of compact thermally efficient designs that would be difficult or impossible to machine. The final technology that offers promise is wireless technology that can reduce the mass and volume required by cabling. Cabling comprises nearly 20% of the NISAR instrument mass. Being able to reduce that contribution offers the most promising technology path forward for miniaturizing the SWaP of SAR instruments.

The workshop also highlighted technology areas that are rapidly evolving within the commercial sector. This includes telecommunications with an explosion in ground station investment. The launch segment continues to evolve with innovations and new competitors across small to heavy lift vehicles, and has started to settle and separate winners from losers. Cloud storage and processing technologies are now a fundamental part of the big data infrastructure, not just for SAR data but for many different types of data across many industries. In all of these cases, the technology will continue to evolve based on market forces. NASA has programs dedicated to monitoring and fostering development in these areas already. SDC has chosen to take the approach that it will interface with the NASA experts in these areas and try to conform to the road maps they envision in their five year plans, rather than directing any resources for specific developments in these areas.

Antenna technology remains a challenging development, as it has for every SAR instrument. The physics of the SAR measurement demands a specific aperture area for proper operation. Thus, the deployed area must have a minimum size dependent on wavelength and the only option for decreasing the stowed size for launch is increasing degrees of deployment complexity. The desire to operate at long wavelengths therefore creates the need for a very large aperture and becomes a significant technical challenge. This challenge is therefore also very dependent on the mission architecture choice. The SDC takeaway based on what was presented at the workshop is that there is no magic bullet for this problem, and deployed reflectors perhaps with some electronic steering in the feed still seems to offer the best mass density for a large deployed area. Though the overall options for antenna architecture do not seem to have changed, there are continuing advancements in implementation that have made incremental improvements to SWaP. Because the antenna will be closely tied to both the spacecraft bus and overall mission architecture, we will evaluate the best technology options for these items on an architecture-specific basis. Thus, rather than investing in technology development right away, the plan is to wait until the trade space starts to narrow in order to focus SDC investments on the most promising architecture options.

The following list is a comprehensive collection of the findings and recommendations given throughout the report, organized by technology area. Please see the associated section in Part B of this document for more context.

On-Board Processing

1. **Finding:** Furthering digital integration on a single package is an enabling technology for SDC and offers the best hope for reducing the mass, power, and volume of the instrument. The improvement is lost with multiple packages because of the power requirements for I/O circuitry. RF SoC FPGA technology provides the clearest path to achieving those goals and should be a core foundation of any instrument architecture explored in this study.
2. **Action (DO Type III RFP):** Perform a study to find the process for using digital electronics that are not space-qualified by the vendor for missions that are class B or class C as the SDC designated observable is expected to be.

Thermal and Hyper-Integration

1. **Recommendation:** Seek any information quantifying how much improvement in mass, power, or volume can be expected from a hyper-integration workflow. Release an RFI seeking specific examples of how hyper-integration might impact the current NISAR electronics architecture.
2. **Recommendation**: Seek more information on the state of using additive manufacturing for NASA space applications and a guideline for the cost associated

with using additive manufacturing processes. Determine if the path for qualification of an additive manufacturing process is well worn or still in the early stages of development.

3. **Action (JPL, Stephen Horst):** Develop an appropriate set of thermal curves that the SDC architecture team can use to gauge the radiator area necessary to accommodate the thermal needs of an SDC mission targeting a 50% orbital duty cycle. The curves should indicate surface treatment and include tails that show the improvement when technologies such as heat pipes or deployable radiators are employed.

Antennas

1. **Recommendation:** Focus the search for an SDC antenna technology on radiating efficiency, areal mass density, and stowage efficiency, with other antenna performance considerations being secondary.
2. **Finding:** There seems to be no technology on the five year horizon that will make a SAR antenna solution any less custom or any less expensive.
3. **Finding:** The need for electronic steering in the antenna will be mission architecture dependent and presents a significant cost and technology hurdle when added to the goals for mass density and efficiency. This feature should be weighed carefully in the architecture trade space and not be added in lightly.
4. **Action (JPL, Richard Hodges):** Once architecture groups are identified with necessary parameters for frequency band and swath width, develop a strawman set of antenna configurations using different technologies. Each configuration should address the implications it would have on the key metrics of mass density, efficiency, and cost, while also addressing other secondary antenna performance parameters as necessary.

Spacecraft Buses

1. **Action (DO Type I RFP):** Perform a study to determine if it is more cost-effective to purchase an off-the-shelf spacecraft bus that exceeds our needs in some performance aspects or to build a custom bus exactly to the needs of the instrument.

Telecom and Ground Stations

1. **Finding:** The technology behind uplink and downlink systems are actively being disrupted. NASA is transitioning to Ka-band for high data volume missions, and has planned a series of technology demonstrations for space-to-ground and relay optical communications. New commercial players and existing firms in the ground segment are establishing new business models and offerings. It does not make sense for SDC to select a data link architecture now while the future of the industry is uncertain. It seems that even under the highest data volume scenarios, there will

exist the capability to get the data to the ground in a timely fashion. We will therefore not let the data link drive the architecture design at this time.

2. **Recommendation:** Monitor advances in optical communications technology and ground segment commercial offerings for impacts on SDC formulation. Engage appropriate ground segment stakeholders once the space segment architecture starts to come into focus.
3. **Action (DO Type I RFP):** Create a white paper contrasting the primary data link topologies that are available, including traditional ground stations, data relays, and fractional leases. Compare the data rate, availability, and cost of optical systems with RF link systems at Ka-band and X-band. This is a low-priority action, to be performed pending staff and funding availability after higher-priority actions are addressed.

Data Segment Technologies

1. **Finding:** The significant technology investments on the science data system for NISAR are largely sufficient to adapt to the needs of a larger system such as SDC. The strategy for where to locate the data within the cloud, for example the improved latency of drawing from a single server location or the data security of spreading data out over multiple servers, is an issue today but may no longer be in five years' time. Therefore, the science data system should not drive the mission architecture development at these early stages.
2. **Recommendation:** SDC should address their baseline architecture designs to science goals. For applications requiring low data latency, SDC should offer additional option tiers that improve data latency and cost associated with each level of latency improvement as applicable.
3. **Recommendation:** Kevin Murphy has developed a ten year plan for Earth Science data. SDC should engage him and work to make sure that anything making its way into SDC consideration is already on the road map for EOSDIS.

Launch

1. **Finding:** The proliferation of launch vehicles leaves SDC with many options for launch and most seem to be operating on a common cost curve. The access to space should not drive the SDC mission architecture, and we should instead focus on the observation needs. We should engage the search for specific launch vehicle costs and options as we narrow down our mission architectures prior to a mission concept review.

Observation Strategies

1. **Recommendation:** Multiple squint observation formations should be included in the SDC trade space. SDC should come up with a way to value the additional science

capability this technique offers and contrast it with the equivalent repeat-times from a constellation system using standalone observations.

2. **Action (JPL, Ala Khazendar):** Signals of opportunity remote sensing data such as that obtained by the CYGNSS constellation may be able to augment hydrology and ecosystems science. This topic should be presented to the hydrology working group at the next research and applications workshop for discussion.
3. **Finding:** While the F-SCAN wide swath technology offers unique abilities to obtain large coverage areas, the wide bandwidth requirement makes it unsuitable for applications at L-band or S-band where bandwidth is limited and split spectrum techniques are needed to correct for ionospheric variation. This makes it unlikely to be useful for SDC goals.
4. **Action (JPL, Stephen Horst):** Formulate a performance model for a sparse aperture instrument that uses wireless synchronization between elements. This performance should be compared with an equivalent-sized traditional aperture instrument.
5. **Action (Langley, Chris Edwards):** Create a white paper outlining the cost of in-space assembly solutions. The paper should highlight the maximum aperture size improvements this technique could offer over traditional deployed apertures as well as the cost associated with this benefit.

Radar Systems

1. **Finding:** Several platforms exist that could serve as a starting point for an SDC instrument. However, careful evaluation must take place to weigh any significant deviations such as frequency band, aperture size, or airborne use that may involve significant cost changes that ripple through the entire system.
2. **Recommendation:** The ROSE-L mission concept is very close to the needs of SDC and is proposed in a similar time frame to SDC needs. The architecture team should open channels of communication for possible collaboration options and ways that NASA might augment or further enable this mission as one architecture possibility.

Commercial Data

1. **Recommendation:** Commercial data seems best suited to meeting the applications goals of SDC, particularly for disaster response or geohazards needs. Develop a scenario where commercial data purchases are used to provide low latency responses to event-driven applications on top of a background collection system for science.
2. **Recommendation:** Commercial X-band data can provide valuable augmentation for cryosphere science. The architecture study team should explore data purchases for this purpose, particularly for COSMO-SkyMed and Iceye data that is already offering data for purchase. Additional systems should be considered as their data becomes available for investigation.

Technology Gaps

1. **Recommendation:** Technologies that would use wireless communication to reduce cabling mass were not explored in this workshop. Explore the options currently out there and determine if this technology has a role to play in any of the proposed mission architectures.

Part A: Context

Earth Science Decadal Survey

NASA currently coordinates the direction of its Earth Science program through the decadal survey process. The final report from this process seeks to form a community-driven consensus on the priority of science questions and the missions or observations needed to support those questions across the gamut of science fields pertinent to NASA's objectives. In 2007, the DESDynI mission was identified as one of the highest priority missions to observe changes in height of solid surface down to millimeter-scale using repeat-pass SAR interferometry. Through the crucible of development this mission became NISAR, a partnership with the Indian Space Research Organization (ISRO) set to launch in 2021 with a three year prime mission. When it launches, NISAR will make up the largest contribution to the program of record (POR) for repeat-pass SAR interferometry observations to date.

The 2017 decadal survey has recognized the science value of these measurements and sought to expand that capability over the next decade by achieving faster repeat times, longer mission durations, and continuity with the NISAR program [1]. This observation, titled Surface Deformation and Change (SDC), has been appointed as a designated observable (DO), the highest priority given by the survey. Specifically, the SDC observation seeks to take repeat times for interferometry down from twelve days for NISAR to something in the sub-weekly range, which might be between three and six days depending on the science. It also seeks to explicitly address the applications of interferometry data, such as geohazard monitoring of Earthquakes, floods, or fires that was only handled on a best effort basis for NISAR. It seeks to achieve this with a cost to NASA of around $500M from development through launch and does not include launch costs.

The process of the 2017 decadal survey has changed significantly from its predecessor in 2007. Whereas the 2007 survey designated the mission for implementation, the 2017 survey designates the observation. This distinction is important because it makes no presumptions about the mission architecture, which could include things like number of spacecraft, swath width, and viewing geometry. It also follows that we must create distinct nomenclature to ensure the separation of mission *requirements* from observation *capabilities*. In the DO vernacular prescribed by NASA, each mission architecture provides a set of capabilities that will meet a certain subset of the observation objectives laid out in the decadal survey. Requirements are not levied until a final mission architecture is selected by NASA and the ability to levy requirements remains under the authority of NASA headquarters and not any study teams they commission.

The impetus for the change in the decadal survey approach lies in trying to increase the engagement of specialists to ensure that the best architecture for the observation is established. This philosophy enables selecting contributors to the decadal survey who understand the translation between science and observation, while a separate, more specialized group, will be tasked with identifying the best translation from observation to hardware. This second group does not necessarily have a perfectly overlapping skill set with the first and therefore the combined working groups can deliver a better value to NASA for their investment. The second group to translate between observation and mission architecture has been commissioned by NASA for each of the highest priority DOs as architecture study teams.

SDC Architecture Study Team

The SDC architecture study team is a multi-center NASA group tasked with selecting an optimal mission architecture to meet a maximal set of the SDC observation objectives. The study team is led by Paul Rosen of the Jet Propulsion Laboratory (JPL) with additional participation from the Goddard Spaceflight Center (GSFC), Ames Research Center (ARC), Langley Research Center (LaRC), and Marshall Spaceflight Center (MSFC). Gerald Bawden and Charles Webb are the Program Manager and Program Executive, respectively, representing the interests of NASA headquarters in this endeavor.

The architecture study team has developed a five year plan to bridge the observations requested in the decadal survey to a full-fledged mission concept review ready to start preliminary design in Phase A. The plan follows the concept maturity level (CML) framework developed by JPL's concurrent engineering center [2]. This plan is highlighted graphically in Figure 1.

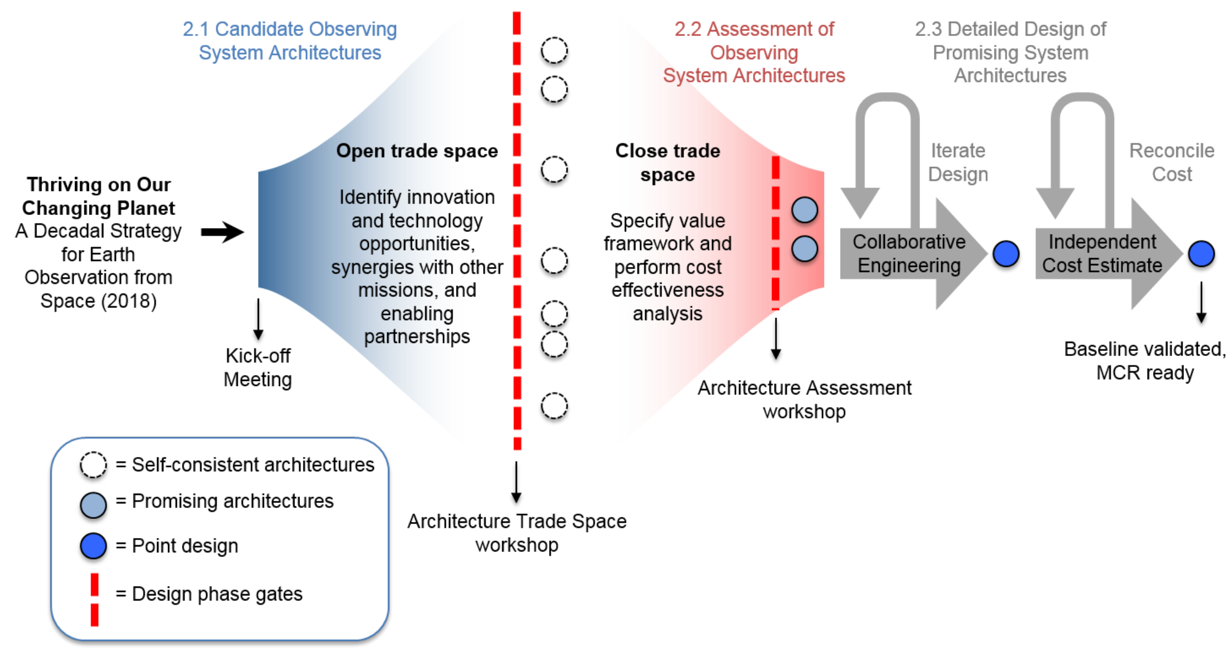

Figure 1. The CML framework applied to the SDC mission architecture study.

The plan starts with a set of kick-off meetings to get everyone on the same page for the parameters of the study. This is followed by an expansion of the trade space to brainstorm as many architectures as possible that might meet some significant subset of the SDC measurement objectives as defined by the science and applications traceability matrix (SATM). The architectures defined in this phase should be self-consistent with a basic understanding of high level performance and resource usage but do not need to have significant depth to their design in order to maximize the number of mission architecture options. Once this process is complete, we will start narrowing the trade space by applying a value assessment that weighs the resource usage of the instrument with the value of the science it generates. The definition of that value framework must also be developed by the architecture study team prior to its application. Once the field of missions has been narrowed to two or three finalist architectures, a more detailed design analysis will be performed by a concurrent engineering team to provide final refinement for each concept. These will then go to NASA headquarters for selection of the final mission architecture, which will then become the mission concept for SDC. The mission concept will be released with an announcement of opportunity (AO) to solicit proposals for the various pieces of the mission system. Mission management will likely be directed by NASA. The current timeline for the entire SDC mission concept selection process is five years.

The purpose of this structure for selecting a mission architecture is to ensure the best possible transparency and allow open engagement from the community who will use this data and build the necessary systems. As such, many of the gates throughout this study period will use a workshop format to provide recommendations to move the study forward. However, the study is a consensus-driven process and prone to paralysis if the pool of decision-makers becomes too large. Therefore the actual decision-making process for the study team will use those developed by NASA's concurrent engineering centers with the core architecture study team as participants. At JPL, that concurrent engineering capability breaks down into two flavors run out of the JPL Innovation Foundry [3]. A-Team sessions focus on brainstorming discussions and the ideation process, while Team-X sessions focus on design trade-offs and the implementation process. Both center around a set of core principles: bringing together a minimum set of subject matter experts from different fields to operate on a shared set of data and constraints, with the goal of identifying the consensus best choices for the study from a field of options.

As previously mentioned, workshops will provide the vehicle for a larger group to influence the direction of the architecture study and will be held around critical decision points. Following the initial kick-off meeting for the study team, two workshops have been held to get the process started. The first was a research and applications workshop designed to start refining and detailing the SATM whose bare bones structure was given in the decadal survey. The second workshop focused on the technology landscape supporting SAR missions and what might be possible within the SDC timeline and is the focus of this report. Other workshops will follow as the work proceeds. Coming to a community consensus on the SATM will take several workshops, town halls, and conference sessions throughout the study period. We will also hold architecture workshops both at the conclusion of the architecture expansion phase and the contraction phase to be as open about the process as possible.

SDC Technology Workshop

The SDC technology workshop was an introduction to the technology developments impacting SAR mission design over the past ten years to members of the SDC architecture study team, many of whom last considered new technologies during the formulation of DESDynI/NISAR. It also introduced the SDC mission to the engineering community that will eventually end up building the components of the mission systems. The workshop had two primary objectives: (1) to define a technology road map for the next five years that could prepare relevant technologies for use in an SDC mission, and (2) to assess the trade space for currently available technologies that could help the architecture study team evaluate competing technologies. Both of those goals are communicated in Part B of this document.

The road map identifies technologies that might be suitable for SDC goals. It starts by identifying key technology areas for the SDC mission, followed by identification of several technologies currently disrupting that area for consideration. NASA requires that technologies under consideration should be mature by the time the SDC mission gets to the implementation phase [4]. At NASA, this evaluation is done via the technology readiness level (TRL) rubric [5]. A TRL 6 designation indicates a technology's maturity by demonstrating a high fidelity prototype in a relevant environment for the mission. The road map assesses the current TRL for each technology and also attempts prognostication of where it will be in five years' when SDC hopes to exit the formulation phase of the mission. We also address whether the technology requires NASA assistance to advance or if market forces will propel it forward without NASA intervention, an important distinction in a maturing field where the resources of a single trailblazing entity is no longer effective relative to the collective forces guiding commercial interests. This information will help the architecture study team assess what will and will not be ready in time to support the SDC mission.

The trade space evaluation compares resource usage of different technologies within the same technology area. Traditional resources for consideration are size, weight, power, and cost (SWaP+C). Performance is another resource consideration that each technology area will have a unique way of grading. Showing the relationship between these resources can help the architecture study team evaluate the suitability of a technology for a given architecture. We expect this evaluation will highlight optimal use scenarios rather than identifying a technology as "better" or "worse" than any other. In many cases, establishing a firm estimate of these resources can be difficult. We will therefore seek to establish relative relationships between them rather than establishing absolute estimates.

There are no shortage of technology disruptors to consider. As we will highlight in Part B, commercial activity in spaceborne SAR has quickened the pace of innovation around an unforgiving set of physical constraints required to make the SAR measurement. The event organizers made a best effort to include a range of technologies that capture the spectrum of technology possibilities for each mission segment with a focus on segments that are most likely to improve the ratio of performance to resource usage on the mission architecture as a whole. But we hold no illusions that the technologies considered here are comprehensive. The workshop had a broad scope and limited time, while the rate of innovation is equally impressive and daunting.

The SDC technology workshop was held May 20-22nd, 2019 at the Pasadena Convention Center, at the same time as the Space Tech Expo. Although the SDC workshop was not affiliated with the event, the Space Tech Expo brings technologies from across the aerospace industry to Pasadena in an exposition style format. The synergies of this event with the SDC goals allowed us to engage a broad swath of world-renowned experts for the SDC workshop who were already in the area for the Expo. The workshop was broken into sessions across two days with most sessions using a panel-style format. The panel consisted of technology experts in the field aided by a moderator. The target audience for the panel consisted of the SDC architecture study team, representatives from NASA's Earth Science Technology Office (ESTO), and other NASA-affiliated guests. The core collection of this audience has been designated the SDC technology steering committee and comprises the authorship of this report. During the session, each panelist was given a ten minute lightning introduction where they introduced themselves and the technology they represented. This round robin then followed with a question and answer session directed by a moderator that sought to bridge the gap between the technology and its potential application for SDC. This two way interaction was the key component of the workshop. In addition to the main room, there were also two smaller rooms available for breakout discussions. The contents of these discussions were private and not captured but also aided in building an understanding from all sides with respect to the intersection between SDC and the aerospace technology landscape. The agenda for the workshop is included in Appendix B of this document for reference. A third day of discussion was held with only the SDC technology steering committee to discuss the outcomes of the first two days of discussion, and are the basis for the recommendations outlined in this report.

Figure 2: Discussion during the on-board processing session.

Figure 3: The SDC technology steering committee was placed front and center to foster a two-way engagement with the panelists.

Continuing Community Engagement

The SDC architecture team is deeply appreciative of the interest, time, and energy that we witnessed at the technology workshop. The SDC study team would like to see that engagement continue throughout the mission architecture development process. As a directed observable, SDC will have the ability to leverage two forms of engagement with the aerospace technology community. The first is through a request for information (RFI). During the concurrent engineering sessions it is very likely that the architecture team will realize it needs more detail on a particular technology area. The SDC study team intends to gather this information by releasing an RFI to all those on the particular mailing list for that area. Sign-ups for the mailing list were available at the workshop and are now also available on the SDC website. An RFI is not binding and simply asks for more information from those willing to give it.

The second method of engagement is through a request for proposal (RFP). The directed observable teams will have access to NASA funds for the purposes of furthering technology development in a critical area. This funding is in addition to the traditional technology development vehicles offered by ESTO such as ACT and IIP. RFPs will be officially released through the NASA science mission directorate (SMD) and will also be posted to the SDC website.

Part B: Technology Solutions

On-Board Processing Technologies

The exponential growth of digital computing expressed by Moore's Law is well known, even to the general public. In aerospace applications, this growth has been tempered by the harsh operating environment, particularly the effects of ionizing radiation. Furthermore, the expense of spaceflight development and operations has built a very conservative risk posture throughout the industry. Systems integrators such as NASA have traditionally required their component manufacturers to guarantee operation for a particular environment under a penalty of financial responsibility for any losses incurred due to failure. This approach has predictably produced a line of space-grade components that are very robust, but also very expensive and several technology generations behind the current state-of-the-art in terrestrial applications.

For digital logic devices, performance is expressed at the highest level by the lithography node it uses. Smaller gate sizes lead to faster device operation and denser integration. The current state-of-the-art commercial nodes use 14 nm gate widths with plans to reduce to 7 nm nodes over the course of the next five years. In contrast, the current state-of-the-art space grade floating point gate array (FPGA) from Xilinx, a type of reprogrammable hardware logic historically favored by NASA missions, uses a 65 nm node five generations behind the commercial 14 nm offerings. Support for a new space-qualified part using a 20 nm node is expected within the next five years. It is important to keep in mind that companies are not developing new product lines specifically for space applications; the market size is too small to justify the very high development costs. Instead, companies are repurposing existing commercial product offerings after going through a rigorous environmental qualification process designed to make it compatible with the broadest range of needs within the market. Though there may be small tweaks to the design if any flaws are found in this qualification process, for the most part the space-grade product line begins as an existing commercial product.

This development paradigm points to a possible performance inefficiency for any given space project. If the device manufacturer is only qualifying parts that will fit a broad market segment, perhaps there are current products on the market today that can be suitable for a specific mission need, with potential risks being controlled through block redundancy. This approach would require the project to commission its own qualification program and make its own assessment of risk, rather than relying on a guarantee from the manufacturer. Cost for the part would therefore increase by placing the qualification burden on a single project rather than spreading that burden out across a market of buyers. Also, such an approach would likely only apply to systems that are not mission-critical avionics. Again, the Mars Helicopter instrument has been a trail-blazer in this regard. The instrument cameras rely on artificial intelligence (AI) algorithms to fly the helicopter autonomously. The have turned to their own evaluation of the Qualcomm Snapdragon 820 processor, ubiquitous in cell phones but with no traditionally space qualified equivalent. The digital processing needs of the SDC SAR instrument might also be a good candidate for this new paradigm. As such, the team should consider what a five generation leap forward in technology capability might offer for a mission architecture.

To evaluate this possibility for the SDC architecture study, we invited experts from several different technology areas in digital processing to inform the team of what might be possible. The session was moderated by Ernie Chuang, the digital systems engineer for NISAR intimately familiar with the processing needs for a repeat-pass interferometer. Dave Hawkins from JPL represented FPGA technology and has over 20 years of experience designing FPGAs for NASA projects. Adrian Tang, also from JPL, represented custom ASIC design and has successfully brought this technology to bear on several research programs within NASA. Michael Lowry from Ames Research Center represented machine learning, specifically looking at neuromorphic computing techniques. Finally, Steve McClure from JPL represented the mission assurance perspective as a radiation specialist.

Discussion in this session was lively. While the representative from mission assurance, Steve McClure, did not represent the official NASA position, he personally felt that projects should be able to use commercial parts when it is critical to the science objective. He converted to this position after the past few years of record growth in commercial and academic space solutions that have relied on clever selection and implementation of COTS parts to achieve results on a shoestring budget. In principle, there should be a path for SDC to leverage a specific piece of commercial technology for a space application. But the application will not be free. In addition to the traditional upscreening of the parts, there will likely be additional radiation testing required to demonstrate the functions of the part used for the mission will operate in the expected environment. This is a key point. Particularly with digital technologies, large scale integration is key and most modern computation devices offer a wide array of functionality. It is entirely possible that a part is not offered as a space-qualified product from the vendor because a single function has a latch-up risk. That function can be physically disabled and would be unused in the SDC application. While such a simple scenario is not always the case, allowing the project to make such judgements is a far more flexible arrangement than the vendor who must consider many different customers.

> **Recommendation: Perform a study to find the process for using digital electronics that are not space-qualified by the vendor for missions that are class B or class C as the SDC directed observable is expected to be.**

The drive for more integration in digital electronics is well-established, which leads to lower power consumption. These days, most of the power consumed by a digital processor is taken up by the input and output (IO) drivers needed to drive the electronic signal across an unknown transmission length at the time the chip is designed. Therefore, chip technologies that increase the available number of gates provide an incremental set of improvements. However, a real paradigm shift comes when entire new functions begin to be integrated into the same chip. Such a technology is now available from system-on-chip (SoC) products. For the SDC radar application, RF SoC technology that combines programmable digital logic with analog-to-digital conversion and pre-conditioning could drastically reduce power consumption by eliminating the need for high power consumption IO circuitry between the logic and digitizers. Required volume is also greatly reduced, though at the cost of higher thermal densities as discussed in the thermal technology section. While RF SoC technology could offer significant improvement in instrument SWaP performance, it is not currently on the five year road map to be offered as a space-qualified product from any vendor. This technology is therefore a strong candidate for a project-based evaluation of its suitability for the SDC application.

> **Finding: Furthering digital integration on a single package is an enabling technology for SDC and offers the best hope for reducing the mass, power, and volume of the instrument. The improvement is lost with multiple packages because of the power requirements for I/O circuitry. RF SoC FPGA technology provides the clearest path to achieving those goals and should be a core foundation of any instrument architecture explored in this study.**

If standard commercial products can offer a high degree of SoC integration, then custom-designed silicon solutions in the form of application-specific integrated circuits (ASICs) can take that philosophy to its logical extreme. These chips include only the functions needed for the application and nothing more while also maximizing the utilization on a single chip. Of course, the drawback is that development costs for such an approach are extremely high and extremely risky. For these reasons, no NASA missions to date have used this approach. However, there have been attempts to change this situation. At the workshop, Adrian Tang from JPL presented his successful quick-turn ASIC designs to several NASA research projects. Unsurprisingly, fully scoping and locking down requirements prior to hardware development is key to the success of this approach. Such a restriction would be a significant departure from the design method used for every radar ever built for NASA. The SDC study team does not believe this development will be any different, particularly when requirements are driven by inputs from multiple science disciplines with competing interests, international collaborative efforts with their competing interests are the norm, and the funding landscape remains in a state of near permanent flux. We therefore see the development of custom ASICs requiring adherence to a set of requirements fixed several years before launch to be too risky and too unrealistic for adoption by SDC. However, impressive progress has been made in this area since the last technology survey done for the mission that would become NISAR ten years ago and we hope to see it progress to a point where the turnaround becomes so fast that the requirements can continue to evolve with a simulation testbed and then finalized and manufactured without design defects on the first pass within a year of the instrument need date.

The final processing technology considered for SDC was applying machine learning to on-board SAR data systems; specifically, the application of neuromorphic computing to the vast quantities of radar data collected by the instrument. It is true that SAR instruments generate copious amounts of data that can strain downlink capabilities. Neuromorphic computing maps the lessons learned from neuro-science onto silicon, and can provide a near order of magnitude leap in processing capability for applications requiring classification, discrimination, or perception; the core machine learning tasks. Such a technique could show continued computational growth as the pace of Moore's law advancements in transistor hardware slows.

On the surface this would seem to offer a key cost advantage to a difficult problem in SAR imagery. If the SDC mission had the operating model of most other commercial spaceborne SAR systems than this might offer significant cost advantages. However, SDC must serve not only specific applications that might suit specific classification problems that only downlink processed data products of interest, it must also serve the science community. Many science disciplines rarely have neat algorithms that can classify what they are after, and would certainly not want to lose any of the data collected, even if it would seem uninteresting at the time of collection. For these reasons, SDC wants to downlink the full raw data collection for archiving in the name of future science. On-board SAR processing may be an interesting feature for decreasing the latency of certain hazard response applications. However, given the cost constraints implied by the decadal survey, the architecture study team does not believe pursuing that feature for a narrow slice of the SDC user community would be the most effective use of NASA investment. Machine learning may still have a place for SDC, but it would most likely be in ground processing done in a cloud environment where there are significantly fewer SWaP constraints. Lossless data compression techniques are not favorable for raw SAR data because of its noise-like structure.

Hyper-Integration Technologies

In order to simplify a complex engineering problem, aerospace design has traditionally broken up sub-system elements into discrete units that can each be tested individually and then are handed over fully packaged to higher levels of integration joined with bulky interconnect cables until the system is complete. This solution simplifies organization at the expense of suboptimal resource usage. Redundant packaging and cables add mass, volume, and therefore cost to the mission.

The nascent field of hyper-integration seeks to recover these inefficiencies by ensuring that every physical object within the system is maximizing its utility by serving as many different functions as possible. The canonical example of this design philosophy is the smartphone. Every element of that device serves a purpose and in many cases multiple purposes. The screen shows the display but also provides structural support, environmental protection, and is seamlessly integrated with the speaker, camera, and other subsystems. On the iPhone, the lone external interface serves to deliver power and connect accessories such as wired headphones. The design approach requires close collaboration between subsystems and uses an organizational structure that looks at the system as a whole body rather than as a collection of parts.

To introduce the ideas behind the hyper-integration concept, we had a special lecture on the topic given by Arbi Karapetian from JPL. Arbi provided the vision for incorporating hyper-integration techniques into NASA programs. This has been most notably manifest on the Mars Helicopter instrument slated to launch on the Mars 2020 rover. This instrument had significant mass constraints in order to achieve lift in the Martian atmosphere and therefore significant creativity was needed in terms of resource usage. For example, the batteries providing power to the instrument also form the bulk of the instrument structure, while the electronics forgo traditional packaging to save further mass, meaning circuit boards must also face additional environmental requirements that would normally be handled by aluminum structure.

This change of approach is not a clearly superior path to delivering a product for space. Most examples of successful hyper-integration center on products that have large production runs and iterative development cycles. Smartphones are produced in the millions and come out with a new and improved version every year, giving time for gradual optimizations and merging of functions. This development process also increases risk in the integration and test flow. When multiple functions are intertwined it can force qualification of individual functions to be performed serially, increasing schedule. It could require a problem with one function to rework or rebuild the combined hardware for both functions. It seems likely that such risks would outweigh the benefits when building a single system, unless that system is relatively small and has special circumstances, such as with the Mars helicopter. However, SDC must build multiple systems to meet the coverage objectives without help from another system. The breakeven point where the hyper-integration approach would provide an advantage is unclear, but should be explored further by the SDC architecture study team.

> **Recommendation: Seek any information quantifying how much improvement in mass, power, or volume can be expected from a hyper-integration workflow. Release an RFI seeking specific examples of how hyper-integration might impact the current NISAR electronics architecture.**

An enabling technology for the hyper-integration approach is the improvements in additive manufacturing that enable structures previously impossible to manufacture. The confluence of thermal design and structure is particularly appealing for NASA designs, as will be highlighted in the next section. However, there are many on the architecture study team who would find the risk of incorporating the function of some subsystem into structural elements a very risky approach. With the exception of additive manufacturing, the organizational challenges and risk posture of the mission are likely more challenging hurdles to implementing a hyper-integrated design approach than technical issues. The SDC architecture study team will need to carefully weigh these factors if it is to meet the cost restrictions of an ambitious mission while also minimizing risk.

Thermal Technologies

In the vacuum of space, systems must manage their operating and non-operating temperatures without the aid of convection cooling typically available for terrestrial applications. This limitation poses a significant challenge, particularly for systems drawing large amounts of power such as a radar. In fact, the capacity to reject heat directly limits the operating duty cycle of many orbital SAR systems. For a mission concept that is focused on coverage and coverage rate, this limitation can become a significant cost driver.

The problems posed for heat rejection are exacerbated by the drive to smaller spacecraft. For otherwise identical radar designs, a configuration change to reduce the size of the instrument and the spacecraft will simply increase the thermal density of the instrument as a whole while providing less area to radiate heat to cold space. The same is true for things like digital electronics integration. Here, the drive to more integration has the benefit of reducing overall power consumption and mass, but the reduced footprints of the integrated packages means that the thermal density around the part will go up in many cases. Thus, technologies that can improve thermal transport and rejection are both critical for SDC objectives and have the potential to be mission enabling.

The panel that assembled at the workshop to help the SDC architecture study team grapple with this problem included Perry Knollenberg from Northrop Grumman, Ben Furst from JPL, Baratunde Cola from Carbice, Scott Schick from Thermal MAnagement Technologies, and Raul Polit-Casillas from JPL. The panel provided several different viewpoints from research perspectives to industry and manufacturing perspectives.

Two phase thermal technologies are one potential solution to the heat transport problem. JPL is developing several variants of this technology that can support the needs of both large spacecraft and small spacecraft down to CubeSat size. The driving force behind these technology improvements is leveraging structures that can only be built using additive manufacturing techniques. One variant of this technology is a passive two-phase system that relies on the capillary effect caused by the transition between evaporation and condensation to move vapor and fluid through heat pipes. The application of additive manufacturing in this realm enables building conformal structures to nearly any size box or chassis, and can transport up to 100 W/cm^2. The technology currently exists as a bench prototype and therefore is at TRL 4, but could advance to TRL 6 within a couple of years if given the funding to demonstrate it in a relevant environment. A larger variant of this technology uses an active pump to move the fluid and vapor. Such an arrangement will increase the thermal capacity and control of the system but increases the complexity and size of the system, therefore costs would also likely be higher. An active system is unlikely to be suitable for spacecraft smaller than 200-300 kg class.

Carbon nanotube technology offers another solution to heat transport between structural interfaces. Carbon nanotubes offer excellent heat transport along the tube structure, and the Carbice Corporation has found a way to manufacture this material at low cost and in sheet form to use as an interface material between two structures [6]. The Carbice sheets achieve a thermal conductivity of approximately 200 W/(mK), roughly equivalent to the aluminum that comprises most structures for space. The sheets can be manufactured in a variety of thicknesses and have a degree of elasticity that eliminates voids in the interface. Furthermore, Carbice has developed an adhesive using the same nanotube material that exhibits no increase in thermal resistance. This feature provides a number of logistical advantages such as easily being able to rework and replace boxes during integration that have traditionally been time intensive and costly. Carbice material has been demonstrated at TRL 9, but has only recently come on the market in the past year or two. It is ready for incorporation into any thermal design that requires interfacing two structures.

As described in the previous section, multi-functional structures take the opposite approach to thermal management. Rather than improving the interfaces between structures, this approach seeks significant mass reduction by combining structure into a single entity that serves multiple purposes. This approach to hyper-integration of many sub-systems is particularly well suited to thermal technologies. Thermal hardware such as heat pipes, heat straps, or thermal storage devices such as phase change material could all potentially double as structural elements for the instrument or spacecraft. For more information on the trade space offered by leveraging multi-function structures, please refer to the section on hyper-integration technologies.

Once heat is transported away from the source, maximizing heat rejection from the spacecraft is also an important consideration in the thermal equation. To first order, the energy radiated to space is a function of the area combined with the solar absorptivity and emissivity of the surface material. A list of thermal properties for common aerospace surface coatings can be found in [7], and should be sufficient for planning purposes. Innovation in thermal coatings involve materials with a dynamic emittance that changes with temperature to regulate the internal temperature of the spacecraft systems. Advancing the TRL on such materials to 6 is in all likelihood beyond the five year timeline for SDC. Louvers provide similar thermal control through mechanically adjusted flaps and NASA has demonstrated to TRL 6 passive control using bi-metal springs capable of being sized small enough for use on a CubeSat [8].

Increasing thermal radiating area is another way to get more heat out of the spacecraft, but as the economics drive to reduce spacecraft volume and mass, there is invariably less surface area available to radiate heat. Thermal Management Technologies has developed a deployable radiator that can provide additional surface area to radiate up to 100 W though size adjustments are possible. Heat is transferred through the radiator via hinges with low thermal resistance. The passive thermal control technology has been demonstrated to TRL 6 through the SBIR program with the full system including deployment and release mechanisms evaluated at TRL 4.

Though these technologies all enable improved thermal performance that may ultimately lower the mission cost, the cost of the thermal system itself will necessarily increase. For some technologies like the Carbice interface sheets, the cost increase is minimal, with only the additional cost of the material and no change in the way the system is designed. In order to implement hyper-integration techniques, the process requires a significant change to the traditional NASA organizational structure to employ more collaboration between engineering disciplines with a cost structure that is hard to gauge. On one hand there is more up front cost for development, but particularly when manufacturing multiple spacecraft, those costs get distributed and the lower cost of production may lead to identical or even lower total cost. There is general agreement that the most expensive part of these technologies is qualifying the manufacturing processes, particularly when additive manufacturing is involved.

> **Recommendation: Seek more information on the state of using additive manufacturing for NASA space applications and a guideline for the cost associated with using additive manufacturing processes. Determine if the path for qualification of an additive manufacturing process is well worn or still in the early stages of development.**

The SDC architecture team is also mindful of the difference between a technology readiness evaluation of TRL 6 and the readiness for manufacturing. Particularly when building in quantities greater than two, a technology will need to be able to be produced and tested with greater reliability than prototype hand tuning techniques often allow. Technologies that are sensitive to manufacturing variation will end up driving cost when building several copies and therefore must be a consideration in technology evaluation. This is true for any technology area, but we are particularly concerned about this aspect for active heat loop architectures requiring significant supporting hardware such as cryocoolers and pumps that may be prone to failure.

The architecture team will also need to assess when these performance improvements justify the increased subsystem costs. To that end, the team should develop a series of curves highlighting the improvement in mass and required radiator area for power levels typical of a SAR instrument designed for SDC. Such curves should provide a ready guideline for when a design starts to get outside the realm of passive thermal management and requires more exotic solutions.

> **Action (Stephen Horst, JPL): Develop an appropriate set of thermal curves that the SDC architecture team can use to gauge the radiator area necessary to accommodate the thermal needs of an SDC mission targeting a 50% orbital duty cycle. The curves should indicate surface treatment and include tails that show the improvement when technologies such as heat pipes or deployable radiators are employed.**

Antenna Technologies

Antennas present a unique challenge for synthetic aperture radar (SAR). In order to form an image without corruption from ambiguities in range or Doppler, a minimum aperture area must be met that is proportional to the wavelength. These large aperture antennas impose significant mechanical challenges in terms of launch stowage, mass, and physical deformation of the antenna surface under varying on-orbit thermal conditions. In addition, the inherent space exposure of an antenna introduces radiation hardness requirements that can limit options for antenna materials. Equally important, but less obvious, are the inherent RF design challenges imposed by radar requirements. These may include antenna efficiency, pattern requirements (beam shape, sidelobes, cross-polarization, etc.), bandwidth, beam scanning, and high power handling. Meeting these challenges invariably requires a custom designed antenna, often using a new design concept.

The SDC open trade space study approach (Figure 1) impacts antenna technology selection because the wide range of potential radar system architectures leads to a correspondingly wide range of antenna requirements and potential solutions. Instrument options can range from large NISAR-class satellites to a constellation of CubeSats. Identifying innovative technology opportunities does not translate into selection of candidate antenna designs. Instead, the innovation opportunities are actually generated by the technologies available to create an antenna design. From the broadest perspective, this would include a range of deployable antenna technologies, formation flying a distributed aperture created by a constellation of SmallSats, robotic assembly or manufacturing of an antenna in space, and autonomous satellite assembly to create a large aperture. Each of these alternatives calls for a unique antenna design solution.

The past several years have seen the rapid development of innovative antenna designs that were enabled by advancements in underlying technologies. Most of these antennas represent a rapid evolution of historical design concepts, made possible by advances in computer-aided design and analysis methods, modern global optimization (genetic algorithm, particle swarm, etc.), manufacturing technology (additive manufacturing, micromachining, robotic, wafer scale integration of phased arrays, etc.), materials science, and engineered electromagnetic materials (artificial dielectrics and metamaterials). In some cases, this evolution has morphed designs to the point where they are perceived as new design concepts. This trend represents a paradigm shift in the antenna design process. It is now possible to rapidly adapt and optimize antenna designs – or hybrid combinations of known antenna designs – to meet unique radar requirements, even if the antennas do not have specific flight heritage.

With this background, it was necessary for the antenna panel to take a somewhat different approach relative to the other technology areas. There was no attempt to identify and pigeonhole specific antenna designs for particular mission classes, with the aim of projecting the technology improvement over a five year period. Instead, the antenna panel aimed to present the range of available antenna technologies, with examples illustrating the current state-of-the-art, and provide an indication of future growth possibilities based on current trends. To accomplish this goal, the following experts in key technology areas of interest for SAR radar were assembled:

- **Prof. Yahya Rahmat-Samii** is a Distinguished Professor and holds the Northrop-Grumman Chair in electromagnetics in the UCLA Dept. of Electrical Engineering. Prof. Rahmat-Samii is a Life Fellow of the IEEE, a member of the National Academy of Engineering, and has received numerous awards for his engineering work. He is a world renowned expert in reflector antenna design, and widely recognized for his research into the use of optimization methods in antenna design and other antenna technologies.
- **Prof. Sembiam Rengarajan** is Chair of the Department of Electrical and Computer Engineering at California State University, Northridge. He is a Life Fellow of the IEEE and Chair of USNC-URSI. Prof. Rengarajan is a world renowned expert in the field of slotted waveguide array antennas and also widely recognized for contributions to computational electromagnetics.
- **Mark Thomson** is Chief Engineer at Northrop Grumman Astro Aerospace, and a former Chief Engineer at NASA's Jet Propulsion Laboratory. He is an inventor and technology development PI in the field of very large precision deployable structures. Mr. Thomson invented and developed the well-known AstroMesh® antenna. His JPL projects included the main radar and radiometer antennas for SMAP, SWOT, NISAR, Europa and numerous CubeSats, including RainCube. Mark holds a BS in Mechanical Engineering from the University of Southern California.
- **Gregg Freebury** is the founder and CEO of Tendeg and has over 30 years of experience in aerospace, satellite and aircraft vehicle design, analysis, and test. Before starting Tendeg, he held senior engineering positions in Northrop and consulted specifically in the space deployables field for over 20 years. He has designed and developed numerous commercial products and been awarded 6 patents related to space deployables.
- **Todd Pett** of Ball Aerospace is a Staff Consultant and Technology Area Lead responsible for microwave technology, and manages the Microwave Tech Initiative chartered with the development of innovative technologies for microwave Earth remote sensing. Mr. Pett holds 9 patents and has over 38 years of experience in microwave engineering, antennas, and telecommunication system engineering. Mr. Pett holds a B.S. degree in Physics and a M.S. degree in Electrical Engineering.
- **Dr. Richard Hodges** is a Principal Engineer at the Jet Propulsion Laboratory and a Life Senior Member of the IEEE. He was Supervisor of JPL's Spacecraft Antennas Group from 2002-2018 and PI of the recent ISARA mission. Dr. Hodges designed the first two reflectarray antennas flown in space (ISARA and MarCO), the original NISAR offset-fed scanning reflector, the SWOT reflectarray and others. He previously worked at Raytheon where he led development of the world's first decade bandwidth phased array (DARPA RECAP program). He also developed numerous electronic scanned arrays and waveguide slot arrays for both space and military

airborne radar applications. He holds B.S., M.S. and Ph.D degrees in Electrical Engineering.

As these biographies indicate, the panel includes expertise in both antenna RF design and mechanical structures. Both disciplines are, of course, essential because creative antenna designs require a synergistic blend of RF and mechanical engineering. The panel covered two broad antenna technology categories: (1) reflectors and lenses, and (2) array antennas, including active electronic scanning array antennas. There are myriad hybrid combinations of these technologies (e.g. array-fed reflectors, large arrays of reflector antennas, etc.) and it is not practical to cover all of these in a short briefing. It should be noted that, while not explicitly listed here, additional antenna technologists were contacted who indirectly informed the summary and overview presentations. What follows is a brief summary of the antenna technology covered by each presenter.

Antenna Presentation Summaries

Richard Hodges introduced the antenna panel with a brief overview of current antenna technology. This presentation included antenna technology challenges relevant to SDC, an overview of large aperture space-based radar antenna technologies, and a discussion of underlying technologies that are enabling new antenna designs. Two important technology trends were highlighted. First, new engineering design methods, manufacturing capabilities, and materials are currently enabling the rapid evolution of antenna designs and the creation of essentially new antenna types. Second, the nexus of small satellites and robotics have enabled new SmallSat distributed-aperture antenna architectures, space robotic assembly, in-space manufacturing, etc. that are only now emerging.

Yahya Rahmat-Samii provided an overview of advanced antenna design research at the University of California, Los Angeles (UCLA). This presentation covered SmallSat deployable mesh reflectors, 3D printed lenses and metamaterial lenses. Of particular interest was the development of new antenna design and analysis methodologies, and particularly the use of global optimization methods (e.g. Particle Swarm Optimization) to create new, advanced antenna designs. The recent research into lens antennas is also noteworthy. Lens antennas historically have not been widely used in the microwave and millimeter wave frequency range. However, UCLA's development of optimized lens RF design, combined with new manufacturing methodologies such as 3D printing, is generating an essentially new antenna technology that can offer unique advantages for some applications.

Sembiam Rengarajan presented a comprehensive overview of waveguide slot array (WSA) antennas, including historical context, key advantages, limitations, and recent advances in the technology. The combined advantages of high efficiency and excellent sidelobe control in a relatively thin, rugged, compact, lightweight, rad-hard structure make WSA antennas attractive for many space applications. These antennas are typically limited to applications that have narrow bandwidth and single linear polarization. Several recent technology developments are noteworthy. JAXA is developing a 4.9m x 0.7m X-band deployable SAR antenna for a 100kg class SmallSat based on parallel plate waveguide slot array technology.

3D printed WSA antennas have been successfully demonstrated which promise to offer very significant reductions in both cost and fabrication time. Tensioned membrane and origami-folded slot arrays have potential to reduce mass and increase stowage efficiency.

Mark Thomson presented an overview of Northrop Grumman Astro Aerospace space deployable products. He began with an overview of the AstroMesh® deployable mesh reflector antenna, including history and current advances. His presentation also covered a range of mechanical deployment technologies that can be used for antennas or other deployable structures. Finally, he described planar deployable truss structures that can potentially serve as the structural backbone of a high aspect ratio planar array or active array antenna, which is directly relevant to some potential SDC architectures.

Gregg Freebury presented Tendeg's recent developments in deployable SmallSat antennas. Tendeg has licensed JPL's 50cm KaPDA deployable mesh reflector, which recently flew on the RainCube 6U CubeSat radar. Tendeg, in collaboration with UCLA and JPL, recently developed the KaTENna 1m offset-fed deployable mesh reflector on a NASA Advanced Component Technology (ACT) project. This antenna design is currently being scaled to 3m diameter with a flight deliverable expected in 2020. Of particular interest is their recent work on a deployable 5m x 1m SmallSat SAR antenna which is being developed on SBIR funding. This antenna has potential application to at least one of the SDC concepts.

Todd Pett presented Ball Aerospace phased array technologies for next generation SAR. This presentation covered Ball's history of phased array antenna developments dating back to the 1970's. Of particular interest was the recent advent of silicon based RF Integrated Circuits (RFICs) – Silicon Germanium (SiGe) MMIC wafer scale phased arrays. This technology promises to enable very significant active array cost improvement that could potentially be a game changer for certain applications. Note that there were separate discussions of SiGe phased array technology with Prof. Gabriel Rebeiz of University of California, San Diego, who pioneered this technology.

Antenna Technology Findings

As discussed on workshop day one in the "Technology Workshop Discussion Framework", the current SDC study encompasses a wide range of candidate architectures (e.g. Dispersed Wide Swath SAR Constellation, Distributed SAR Constellation, Grouped SAR Formation, etc.). Implementation of the various architectures encompasses six satellite size classes ranging from 2000-2500kg Jumbo Satellites (e.g. NISAR) to 5 kg CubeSats. It is not feasible to provide specific technology recommendations for such a broad range of potential instruments.

Nevertheless, it seems inevitable that any SAR antenna will ultimately be a custom design tailored to meet specific radar performance and spacecraft accommodation requirements. Antenna efficiency, aerial mass density and compact stowage will be a challenge for any design. Many new antenna designs have appeared in recent years, and even more are currently in development (although details are not publicly available for some of these developments). For example, the JAXA deployable waveguide slot array and the TENDEG

SAR reflector antenna show promise for instruments that target ESPA-class SmallSats. We summarize this in the following recommendation:

> **Recommendation: Focus the search for an SDC antenna technology on radiating efficiency, areal mass density, and stowage efficiency, with other antenna performance considerations being secondary.**

> **Finding: There seems to be no technology on the five year horizon that will make a SAR antenna solution any less custom or any less expensive.**

Electronic beam scanning presents a unique challenge for SAR applications that require this capability. Active electronically scanned arrays (ESA) must integrate and calibrate a large number of transmit-receive modules (TRM), which historically has resulted in extremely high cost and other technical challenges. However, most traditional SAR architectures primarily require scanning in a single plane (cross-track), which can significantly reduce the number of TRMs, with a commensurate reduction in cost and complexity. The NISAR array-fed reflector is an example. However, this approach imposes demands on the antenna architecture that can limit antenna design options. For example, the JAXA slot array architecture cannot be modified to provide beam scanning (although other slot array architectures show promise). The take-away is that electronic beam scanning needs special attention in the overall SDC architecture selection.

Wafer scale integration of Silicon Germanium (SiGe) active arrays deserves special attention. At a research level, this technology has been shown to dramatically reduce active ESA design time and cost. It appears likely that SiGe active arrays will be adopted for use in 5G systems, which could create opportunities for low cost commercially available parts. Thus, SiGe technology could be a game changer in terms of phased array cost.

> **Finding: The need for electronic steering in the antenna will be mission architecture dependent and presents a significant cost and technology hurdle when added to the goals for mass density and efficiency. This feature should be weighed carefully in the architecture trade space and not be added in lightly.**

> **Recommendation: Once architecture groups are identified with necessary parameters for frequency band and swath width, develop a strawman set of antenna configurations using different technologies. Each configuration should address the implications it would have on the key metrics of mass density, efficiency, and cost, while also addressing other secondary antenna performance parameters as necessary.**

Spacecraft Technologies

Small spacecraft demands for critical space applications are increasing as small satellites are becoming more capable and have the ability to perform more complex missions at lower cost. Small satellites were primarily thought of as being used for validating emerging technologies at lower costs and higher risk profiles. However, a paradigm shift is occurring, where traditional complex missions with a single large primary spacecraft, are now being investigated as missions with more than one small spacecraft at a much lower cost, as is being evaluated in SDC. Small spacecraft systems also provide robustness to single point failures, allow frequent technology refresh, and reduce overall launch costs as secondary payloads or dedicated rideshare opportunities.

The commercial industry has recognized the significance of small spacecraft, and are responding in a variety of ways. More vendors are providing commercial-off-the-shelf (COTS) spacecraft, offering common buses to serve as turn-key solutions for various mission requirements. It is no longer the case that small satellites are cost effective because of the utilization of lower level of qualification and screening of components. Rather, the fast growth of small satellites has created a sizeable market, enabling smaller, more power efficient, radiation tolerant, and precise components to be developed. This positive feedback is spurred by their shorter production time and lower launch costs. Spacecraft assembly-line facilities are also surfacing to accommodate the increasing demand for mega constellations, swarm satellites, and distributed systems.

NASA has also increased its use of small satellites. Given limited budgets, agile solutions utilizing small satellites are increasingly in demand at NASA. There is a logical case for SDC to study the COTS spacecraft trade-space, and the utilization of one or more COTS spacecraft to achieve the SDC goals.

> **Action (DO Type I RFP): Perform a study to determine if it is more cost-effective to purchase an off-the-shelf spacecraft bus that exceeds our needs in some performance aspects or to build a custom bus exactly to the needs of the instrument.**

Five technologists were in attendance at the Spacecraft Session of the Technology Workshop. Austin Williams from Tyvak discussed their CubeSat-focused spacecraft lineup and capabilities. It is important to note that due to the complexity of the SDC objectives, a CubeSat-class implementation of the SDC measurements would most likely not meet Tyvak's existing line of CubeSats, due to a significant amount of NRE that would be required to implement an SDC solution. Reuben Rohrschneider from Ball Aerospace presented the traditional family of BCP Small, Medium, and Large classes. Ball has a significant amount of flight heritage and experience in developing spacecraft for NASA missions. Reuben emphasized Ball's small satellite capabilities, although only a few small satellite missions were presented. Ball intends to continue to develop its platform to incrementally increase capabilities while reducing costs. The Ball small satellites also have an appealing operation class of over five years, which would be useful for continuity of measurements in SDC. Brad Hirasuna from Aerospace presented their spacecraft heritage, families of spacecraft, and facilities. Tim Flora from Sierra Nevada Corporation similarly presented their heritage in space systems and spacecraft, families of spacecraft in LEO and GEO, and particularly small satellite capabilities. During the panel, there was a consensus across all technologists that

During the panel, there was a consensus across all technologists that that the cost of designing a spacecraft is comparable to the cost of building it. For a batch build of multiple spacecraft, there may even an increase in the upfront NRE to plan for the parallel manufacturing. For building two identical units, the companies reported only modest cost reduction on the second unit. A build of multiple, identical spacecraft would not offer very much cost savings until at least three to five spacecraft were built.

All the panelists indicated that their companies were in ongoing discussions with many potential customers. The customers' sensitivity to cost motivates the spacecraft providers to invest wisely in having appropriate offerings. Without a market for a one-size-fits-all spacecraft, where a mass-produced, over-designed bus could serve many customers through economies of scale, each technologist described how their company chose to specialize in a certain range of sizes and capabilities. The customers for these size ranges also have common needs for quality and mission assurance. As an example, the Ball BCP-50 was described as having most of what was needed for many customers, with minor, mission-specific modifications. It would not, however, scale up to host a 100 kg instrument, nor would it be competitive for a hosting a low-cost camera. Either of those cases are better served by other base configurations.

Given the similarity of small spacecraft capabilities presented from the technologists, there seems to be an apparent emphasis in their current developments into improving their small satellite capabilities and lowering costs. At this point in time, all small spacecraft presented in this session are at TRL 9, which gives them flight heritage. However, it should be noted the cost and amount of NRE for these small spacecraft can still be significant for a NASA mission. In approximately five years, we can expect the capabilities for the small satellites to increase and possibly be able to meet SDC mission requirements. However, with the continued emergence of commercial mega constellations and satellite swarms, it is likely to be difficult for SDC to stay competitive and take advantage of the COTS/assembly-line cost savings, if less than approximately a dozen (assuming identical) spacecraft are required, on-top of the rigorous NASA-associated requirements placed on space flight missions and procurement processes..

Telecom and Ground Segment Technologies

Telecommunications and ground segment technologies are essential elements of spaceflight and cross-cut all SDC objectives. These needs are currently met through NASA's Near Earth Network (NEN) and high data volume missions (e.g., NISAR and PACE) have prepared the NEN to support SDC. NASA's NEN includes commercial providers and the growth of NewSpace has resulted in disruption in the commercial market. Amazon Web Services recently entered with a limited number of ground stations tied to their regional data centers, and RBS Signals is a new joint ventures that aggregates and sells excess ground station network capacity.

Four commercial providers and a representative from NASA's Near Earth Network presented at the technology workshop. RBC Signals is an aggregator of excess ground station network capacity, matching customer needs to provider capabilities on UHF, S, C, X, Ku, and Ka-bands. AWS Ground Station consists of 12 ground stations with Ka, X and S-band capability that are co-located with Amazon Web Services (AWS) Regions, allowing users to easily link their data to AWS' 165+ services. Empower Space Alliance is a joint venture by Xenesis, ATLAS Space Operations, and Laser Light Communications to provide optical space-to-space, space-to-ground, and point-to-point communications. KSAT (Kongsberg Satellite Services) provide UHF, L, S, C, X Ku, and Ka-band communications and are building optical services capability. They are a current member of NASA's Near Earth Network. The NEN is NASA's global telecommunications network consisting of a mix of ground stations owned by NASA, partner Federal agencies, and commercial providers (currently KSAT and SSC) providing VHF, S, X, and Ka-band communication.

> **Finding: The technology behind uplink and downlink systems are actively being disrupted. NASA is transitioning to Ka-band for high data volume missions, and has planned a series of technology demonstrations for space-to-ground and relay optical communications. New commercial players and existing firms in the ground segment are establishing new business models and offerings. It does not make sense for SDC to select a data link architecture now while the future of the industry is uncertain. It seems that even under the highest data volume scenarios, there will exist the capability to get the data to the ground in a timely fashion. We will therefore not let the data link drive the architecture design at this time.**

NASA has been on the path toward increasing use of Ka-band downlink communications for several years. This is the near-future for NASA Earth observation data transmission, driven in part by planned high data volume missions such as NISAR and PACE. Optical communications are an emerging technology for Near Earth Down to Earth (NE -DTE) and Near Earth Relay (NE-R) comms. Optical comms offer potentially faster data transmission rates, but are more susceptible to atmospheric effects and require precise pointing, potentially adding cost and technical complexity [9]. NASA's current timeline for optical communications include technology demonstrations for NE-DTE in 2019 and NE-R in 2019-2021; operational systems for NE-DTE and NE-R are expected in 2024 and 2025-2027

[10], respectively. Direct and/or relay optical communications versus traditional RF NE-DTE communications may require some SWaP-C trade studies, but the sense of the session attendees was that SDC may be too early to adopt optical comms for NE-DTE or NE-R, at least as a primary system. Regardless, the sense of the session attendees is that a solution will be available to meet SDC's still-to-be-determined requirements for downlink data volumes and latency, with alternatives available at different price structures. It does not make sense for SDC to decide on a ground segment architecture at this point. The invited panelists also expressed their appreciation for being engaged at this early stage, noting that the ground segment engagement usually comes later in the mission lifecycle, at which point prior decisions limit options and give them less time to plan.

Recommendation: Monitor advances in optical communications technology and ground segment commercial offerings for impacts on SDC formulation. Engage appropriate ground segment stakeholders once the space segment architecture starts to come into focus.

Action (DO Type I RFP): Create a white paper contrasting the primary data link topologies that are available, including traditional ground stations, data relays, and fractional leases. Compare the data rate, availability, and cost of optical systems with RF link systems at Ka-band and X-band. This is a low-priority action, to be performed pending staff and funding availability after higher-priority actions are addressed.

Data Segment Technologies

The NISAR mission anticipated to launch in 2021 will be a game changer for radar-based Earth science. While the Sentinel mission launched in 2014 has already produced a wealth of free and open SAR data for use by the international science community, NISAR will be the first mission to make systematic collection of nearly all land mass around the globe available with updated observations using the same observation geometry every twelve days. The SDC mission would seek to at least triple the data volume generated by NISAR. The ground system to handle this data must be fundamentally different than the systems used to handle other SAR systems with more targeted observation schemes.

The NISAR program has made significant investments in this area along several fronts in order to support the deluge of data that must be continuously processed and archived throughout the mission. This includes the implementation of a back-projection SAR processor capable of handling data from multiple viewing geometries seamlessly as well as a fully cloud-centric compute architecture capable of automatically geo-tagging and ingesting NISAR data to cloud storage for scientific access. Strides are also being made to improve data discovery.

For the SDC architecture study team, the question is how such a system would need to be enhanced for SDC at a point where the NISAR system is not yet complete and operating. To help answer this question, a number of experts were engaged from around NASA and industry familiar with both NISAR and the anticipated changing landscape for SAR data in the global marketplace. The moderator for this discussion was Piyush Agram from JPL and architect of the ISCE processing environment used to process NISAR data. Panelists included:

- Hook Hua from JPL, architect of the NISAR science data system
- Dan Pilone from Element84 and builder of the cloud ingest software for NISAR
- Matt Calef from Descartes Labs
- Xin Li from Orbital Insight
- Derek Edinger from Ursa Space

The commercial companies represented here are all interested in the data NISAR will generate and incorporating those free data products into value-added commercial products that can help any number of industries. The GPS system is a government-backed system with data made available freely to the public. At the time of creation no one had any idea of the breadth of location-based services that would spring up and eventually make GPS technology a key part of daily life. There is a line of thinking that SAR data may follow a similar arc. If end users can interpret optical satellite imagery or precipitation radar data, perhaps systematic processed overlays of SAR data can add to the geographical information data sets used by people with no radar expertise. Such an adoption would provide the market that could fund the collection of scientific data on an ongoing basis, a winning situation for all involved should you believe this line of reasoning.

An alternate viewpoint suggests that the commercial applications are a distraction because they are driven largely by data latency. In terms of commercial value, the data becomes exponentially more valuable the closer it gets to real-time. Whereas science investigations have no latency requirement and the fundamental science will not change whether the data were collected two minutes ago or two decades ago. Introducing a latency requirement on the data can be a significant cost driver for the data system architecture, and SDC is cost-constrained for the ambitious revisit rates it hopes to achieve. This line of reasoning would argue that SDC resources are needed most to satisfy the core mandate to lower revisit times, and any effort to define data latency or consistency in service of commercial applications will end up over-burdening the project and risking failure. We should therefore focus only on SDC internal goals and only give best effort goals for data latency similar to NISAR.

Navigating the line between scientific research and applications is a core dilemma that the SDC architecture team will have to deal with throughout the study. Aside from the question of enabling potential third party commercial applications, there are a host of NASA-driven applications mostly centered around geohazard detection that SDC must directly consider. These applications teams, of which ARIA is the most notable, have provided significant aid during the response to large-scale natural disasters around the world. Balancing their needs with the needs of other science disciplines will be part of the value framework that SDC must derive. From a technology standpoint, we believe the best way to enable decisions in this area is to define tiers of latency service. For example, a candidate architecture may require a particular space segment configuration. The ground and data segments could be designed with the lowest cost and no latency needs in mind. For improvements to data latency, different improvements could be proposed along with the cost difference of making these improvements. These tiers of service along with a better understanding of an applications needs can help best define the data latency SDC can afford.

Recommendation: SDC should address their baseline architecture designs to science goals. For applications requiring low data latency, SDC should offer additional option tiers that improve data latency and cost associated with each level of latency improvement as applicable.

Aside from the regular availability of data over a given area, commercial concerns would also like to see more standardization in the available data products. The variation of data formats and the content of meta data for various SAR sensors make it difficult to apply data from different sensors to a common problem. One of the hallmarks of SAR data maturity will be when one does not bother to mention whether this particular set of L-band SAR data came from NISAR, or ALOS, or Tandem-L because the data is sufficiently uniform to be interchangeable. That day has not yet arrived, but the SDC team members who are also involved with NISAR development hope that the paradigm shift that NISAR is introducing to the data system will move standardization in that direction by necessity because the sheer volume of data that will be made available requires an automated data discovery process rather than a hand-picked one. Still, there are low cost ways that the NISAR team can contribute to making data more readily accessible to non-experts, such as contributing code to open source efforts such as the popular GDAL conversion libraries to enable project-supported standardized access to NISAR and SDC data products.

SAR data must be increasingly viewed through the lens of all Earth-science remote sensing data and not just as a standalone product. Many of the commercial companies on our panel have taken this approach and are focused on providing customers with sensor fusion between optical, hyper-spectral, and SAR data. NASA is also a major player in pursuing this trend and has created programmatic support for it through the Earth Science Data Systems (ESDS) program headed by Kevin Murphy. ESDS is tasked with viewing the NASA Earth Science data archive as a whole rather than as a collection of distinct data sets. In this regard, the SDC architecture study would do well to follow the lead ESDS has put forward to ensure that any SDC data products fit into their ten year vision for Earth data products.

> **Recommendation: Kevin Murphy has developed a ten year plan for Earth Science data. SDC should engage him and work to make sure that anything making its way into SDC consideration is already on the road map for EOSDIS.**

It appears that NISAR is handling the major architectural transition from a hand-picked, locally-operated processing system to an automated and cloud-based solution. An SDC follow-on would largely leverage this investment. There are currently cost-constraining limitations on cloud computing, namely in moving large data sets across cloud server locations around the world, that may impact an SDC architecture compared to the present NISAR architecture. However, given the pace of cloud development it is unclear whether this limitation will still be an issue worth worrying about in five years' time. The best course of action at this time is to keep a watchful eye on developments of cloud-computing with respect to big data and evaluate the need for investments in architectural improvements at that time.

> **Finding: The significant technology investments on the science data system for NISAR are largely sufficient to adapt to the needs of a larger system such as SDC. The strategy for where to locate the data within the cloud, for example the improved latency of drawing from a single server location or the data security of spreading data out over multiple servers, is an issue today but may no longer be in five years' time. Therefore, the science data system should not drive the mission architecture development at these early stages.**

Launch Technologies

The era of "new space" has been driven by innovations in the launch segment promising lower cost access to space. This period of innovation started with SpaceX and reusable launch vehicles and has continued with Rocket Lab, Virgin Orbit, and others focusing on small payloads. Within the five year technology timeframe of SDC, it is expected that there will be a range of launch vehicle options across the spectrum of lift needs that have demonstrated orbital success. However, the technology behind these launch innovations is not of particular relevance to the SDC mission. SDC needs to know how it can best engage these new technologies in order to ensure the most efficient access to space for its constellation of satellites at any size. To that end, the workshop included a special lecture topic on access to space with Jason Jagdmann from the Launch Service Program (LSP) at Kennedy Space Center (KSC), that focused on how the SDC team can best engage NASA's launch services to ensure SDC gets an optimal launch configuration.

LSP currently maintains a fleet of launch vehicles for use in NASA programs through the NLS-II government contract. This fleet includes a spectrum of small to heavy lift options. Current launch vehicles under the NLS-II contract include:

- RocketLab Electron
- Virgin Orbit Launcher One
- Orbital Sciences Pegasus XL
- NGC Minotaur-C
- Orbital ATK Antares
- SpaceX Falcon 9 Full Thrust
- ULA Atlas V
- ULA Delta IV Heavy
- SpaceX Falcon Heavy

Over the next five years, NASA expects to see a host of new entrants from the smallsat oriented Firefly Alpha to interplanetary New Glenn added to the contract. Though with the five year technology horizon for SDC, the study team was encouraged not to baseline a rocket based on its current availability on the NASA contract. Given the level of change currently underway in the industry, it is unclear if these rockets will still be in service by the time SDC gets to the launchpad. For example, it was less than five years ago that ULA announced the end of life for the standard Delta IV rocket, which is having its final launches this year.

Instead of designing a mission within the constraints of a particular rocket, KSC recommends selection of a rocket after optimizing the architecture for other constraints. There is sufficient availability in the launch market that the appropriate vehicle for the architecture can be selected without driving the cost of the mission. This flexibility can extend to whatever number, size, and orbits of spacecraft best meets the SDC architecture.

Finding: The proliferation of launch vehicles leaves SDC with many options for launch and most seem to be operating on a common cost curve. The access to space should not drive the SDC mission architecture, and we should instead focus on the observation needs. We should engage the search for specific launch vehicle costs and options as we narrow down our mission architectures prior to a mission concept review.

The SDC architecture study team sees the best time for this engagement late in its concept development phase after the trade space is narrowed down to a few most promising architectures, but prior to final selection. At this time the team can work with KSC to identify optimum launch vehicles and costs, while also identifying the acoustic and vibration environments that will be necessary to begin design work on the spacecraft.

While the architecture team reserves the right to work directly with launch providers, it recognizes the experience that NASA's Launch Services Program brings to the table. This experience spans both domestic and international launch vehicles as well as vehicles currently under development. LSP understands the launch requirements placed on NASA missions and can work directly with the architecture study team to draft an RFI to industry for any unique launch capabilities that may be required. Furthermore, LSP has collected historical data on actual NASA launch costs dating back many years and can help the study team develop accurate predictions of launch costs. However, the study team has concerns about NASA's traditional launch practices that have resulted in significantly higher launch costs for NASA programs compared to commercial programs for similar spacecraft mass. The team hopes to be able to utilize the best practices utilized by the commercial sector in order to close this gap, and hopes that the LSP will be willing to explore these options with the study team and challenge traditional NASA doctrine where appropriate when the time comes to select the launch architecture for SDC.

Observation Strategies and Technologies

The intent for creating the SDC architecture study team was to ensure that NASA gets the best mission architecture for its investment. In order to achieve this goal, the SDC study team was asked to consider alternative and unconventional approaches to making the measurement. Though duplicating a stripped-down version of the existing NISAR design multiple times is certainly one potential architecture, it should not be the only architecture. The SDC team has established that coherent radar imagery is the only suitable remote-sensing technique capable of making the deformation measurements with the required accuracy for the science. However, there are a wide range of possibilities for observation strategies using that underlying radar technology to make the measurement.

This session within the workshop sought to explore non-traditional ways of making deformation measurements that might lead to unique measurement opportunities or improved cost efficiency for the mission. The panelists represented different technology possibilities, and each was treated on an individual basis. The session was moderated by Razi Ahmed from JPL, an expert on radar measurement techniques with a keen interest in tomographic applications.

Multi-squint Observations

SAR radar observations from multiple squint angles offers a number of possible performance improvements over a traditional system steered to zero Doppler. This technology was presented by Brian Hawkins from JPL who is working on demonstrating this technology on the UAVSAR airborne platform. Once successfully demonstrated, it will be at TRL 6. As part of this concept, three independent SAR platforms operate in relatively close formation along the same orbit, with the center platform steered to a traditional zero Doppler viewing geometry, and the two platforms on the periphery steered to view nearly the same swath at sufficient and opposing squint angles. By observing the same backscatter through different atmospheric paths, the tropospheric error can be measured along with the SAR data and more effectively removed from the data. Uncertainty in the tropospheric delay due to varying water content makes up the largest error source in deformation measurements. Traditionally, the tropospheric contribution to delay is estimated via models, but a technique for measuring this error source would be a substantial improvement in the uncertainty of deformation measurements.

Having multiple squint angles also provides the look angle diversity to form three dimensional deformation measurements. NISAR is a single instrument steered to zero Doppler with a 12 day repeating orbit. For any given point on the ground it will see that spot while on an ascending orbit pass and a descending orbit pass. When those passes repeat 12 days later, interferograms can be formed revealing the deformation along the slant range for both ascending and descending passes. NISAR then takes these two deformation components and uses them to determine the deformation projected onto the direction normal to the surface of the Earth, which is a far more useful metric for scientists. Having two slant directions for this projection means that only two components of deformation can be estimated, and slip or shear deformations cannot easily be seen. By adding multiple squinted viewing angles to the measurement, and combining them with the ascending and descending diversity provides four deformation estimates in slant range with significant angular diversity. These four estimates can then provide a full three-dimensional deformation estimate. This measurement would be a unique augmentation over any previous repeat-pass deformation estimates and would surely open up new avenues for science.

The advantage conferred by this observation technique is fundamentally counter to the mandate to decrease repeat-pass intervals. While decreasing repeat-pass intervals requires spacing out observations with multiple spacecraft, the multi-squint technique uses those same resources to observe a common region on the ground. In other words, for the same number of spacecraft, the multi-squint technique will have longer repeat-pass times because it must dedicate more resources to observe the same region. One of the tasks for the SDC architecture study team will be to establish the relative science value of obtaining three dimensional deformation measurements compared to achieving faster revisit rates.

> **Recommendation: Multiple squint observation formations should be included in the SDC trade space. SDC should come up with a way to value the additional science capability this technique offers and contrast it with the equivalent repeat-times from a constellation system using standalone observations.**

Radar Signals of Opportunity

Spaceborne radar transmitters must be powerful in order to compensate for significant path loss and weak backscatter while still providing detectable signals for the receiver. These transmitters therefore draw significant power from the spacecraft bus and are very heavy while also occupying significant spacecraft real estate for thermal management. This restriction has prevented radar systems from the dramatic size reductions seen in other remote-sensing instruments such as radiometers and cameras that use incoherent, natural radiation sources. However, the Earth today is awash in man-made signals that could be used as coherent sources for a radar instrument. The CYGNSS mission has demonstrated this possibility and used forward scattering from GPS transmissions to measure wind speeds in hurricanes. Cinzia Zuffada from JPL has been using this measurement data to also form surface height estimates at the specular reflection point by comparing the delay formed by the specular ray path at the nadir antenna from a direct path measured at the zenith antenna.

CYGNSS forms its measurement through the creation of delay-Doppler maps which differ slightly from the range-Doppler maps formed from traditional SAR backscatter. Though the instrument uses coherent averaging along track to form a synthetic aperture, it is a nadir-looking receiver and uses this information to form a single measurement more like a scatterometer than a two dimensional SAR image. The GPS signal is intended for one-way transmission to Earth and is, therefore, very weak when it is received by the CYGNSS receiver. The measurement works best with strong specular reflections that come off of water, which differs from the SDC measurement focused on solid surfaces, although certain types of ice and snow can produce strong specular reflections as well.

The architecture of the CYGNSS design does not lend itself well to meeting the bulk of the SDC goals. The GPS signals are too weak to be used as signals of opportunity in a traditional backscatter configuration and there would seem to be few other signals of opportunity near L-band wavelengths that could reliably provide global coverage. However, the technique may provide a useful low cost augmentation for hydrology or ecosystems science. The SDC architecture study team should address this possibility with the science communities at the next research and applications workshop.

> **Action (JPL, Ala Khazendar): Signals of opportunity remote sensing data such as that obtained by the CYGNSS constellation may be able to augment hydrology and ecosystems science. This topic should be presented to the hydrology working group at the next research and applications workshop for discussion.**

F-SCAN Wide Swath Technique

Increasing the swath width of a radar measurement is a known technique for reducing repeat-pass intervals. NISAR uses a SweepSAR technique to achieve a 240 km swath width that exceeds multiple inter-pulse periods through the use of digital beamforming on the receive echo. ScanSAR is another popular wide swath technique that uses electronic steering of a phased array to process multiple patches across the swath at the expense of degraded azimuth resolution from not sampling the complete Doppler spectrum. Thiemo Knigge from Airbus highlighted a third wide swath technique that they call F-SCAN and use as a core technology for the proposed HRWS SAR mission for the German Aerospace Center, DLR.

The F-SCAN technique uses the natural frequency dispersion of slotted antennas to steer the antenna beam in the cross-track direction. Thus, the signal reflecting off of the near edge of the swath is a lower frequency than the reflection from the far edge of the swath. In this manner the radar can tailor its swath width by utilizing more bandwidth than required for the resolution. For example, if a properly designed instrument increases its bandwidth by a factor of n, it will be able to achieve a swath improvement by a factor of n-1. The ability to tailor the swath width on demand enables some improvements in image quality such as better signal-to-noise ratio and noise-equivalent σ_0.

The need for extra bandwidth is an issue for longer wavelength radars due to strict NTIA spectrum controls. This is a significant problem at L-band and S-band that are optimal for SDC for temporal decorrelation and foliage penetration. The allocated bandwidth at these frequencies does not provide much room for extra bandwidth to cover the resolutions requested by the decadal survey. Most measurements in the survey request 10 m ground-range resolution, which requires approximately 25 MHz of bandwidth. In contrast, the NTIA allocation is only 85 MHz at L-band. This might enable a factor of 3 bandwidth increase and in turn a factor of two increase in swath over the standard SAR swath width.

However, this width would still be less than that achieved by NISAR. S-band offers slightly more bandwidth with 200 MHz of spectrum available, and bandwidth could be decreased to 17 MHz if the science community would accept 15 m resolution for the same measurement goals.

In the best case scenario, S-band could offer a ten-fold increase in swath at 15 m resolution. But there remains an additional hurdle. NISAR relies on a split spectrum measurement to mitigate ionospheric effects from the atmosphere. Implementing this technique requires frequency diversity. Therefore, NISAR has implemented its science chirp over 20 MHz at one end of the 85 MHz allocated band with a 5 MHz split spectrum chirp at the other end. Expanding the bandwidth to narrow this diversity would degrade the ionospheric estimation and likely have unacceptable consequences for overall deformation measurement performance.

Finding: While the F-SCAN wide swath technology offers unique abilities to obtain large coverage areas, the wide bandwidth requirement makes it unsuitable for applications at L-band or S-band where bandwidth is limited and split spectrum techniques are needed to correct for ionospheric variation. This makes it unlikely to be useful for SDC goals.

Wireless Time Synchronization Technology

When multiple spacecraft operate within close proximity to one another, communication between them becomes critically important. One possible space segment architecture could use a number of CubeSat-sized elements flying in close formation to form a sparse aperture for SAR image formation with a corresponding degradation in ambiguity levels. In such a scenario, a key challenge will be the inter-satellite communications to synchronize the timing between the elements. Todd Faulkner and Daniel Goff from ENSCO have developed a coherent wireless link technology that could address these problems.

Coherent link technology (CLT) enables synchronization of clocks at a distance using only wireless communication signals. It specifically uses a coded waveform and Doppler shift to make its estimates. Currently evaluated at TRL 4, the prototype hardware can currently synchronize two clocks to a precision of 12 ps. The technology has the additional capability to determine the position of multiple clocks in the formation to help with formation control and maintenance.

For SDC needs, if it is assumed the clock needs to be synchronized to 1/36th of a wavelength for proper performance of the sparse array, then the CLT design will need to provide 7 ps timing accuracy at S-band. An initial timing deviation analysis suggests this is possible. There is a fundamental trade-off in the design between the clock synchronization accuracy and the update rate with more accurate synchronization producing updates less often. This trade-off would need to be carefully weighed between clock sync and position knowledge functions. Developing the specific architecture, improving the filter design, and testing for relevant environments would all be required to bring this technology to TRL 6.

In order to move the CLT technology forward for SDC, the first step is to define a radar performance tool that can estimate the performance of a sparse array radar instrument. This model should include clock synchronization effects in order to accurately bound the capabilities needed by CLT. Once these boundaries are understood, the design balance between accuracy and update frequency can be properly tuned, and the appropriate filters can be specified.

> **Action (JPL, Stephen Horst): Formulate a performance model for a sparse aperture instrument that uses wireless synchronization between elements. This performance should be compared with an equivalent-sized traditional aperture instrument.**

On-Orbit Robotic Assembly

In Space Assembly (ISA) could provide significant benefits to the space segment components of a SDC architecture and enable new capabilities, however, ISA also presents challenges for implementation of SDC. Some benefits of SDC architectures utilizing ISA include:

- Enabling aperture sizes not possible today
- Enabling frequencies not possible today
- Flexibility in different implementations
- Increased packing efficiency and flexibility for launch
- Potential for extended lifetime and risk mitigation via servicing and repair

While ISA has not been common in Earth science missions, it has become a focus area in other disciplines. In preparation for the 2020 Astronomy and Astrophysics Decadal Survey, the NASA Science Mission Directorate Astrophysics Division chartered the in-Space Assembled Telescope (iSAT) study to investigate the viability of ISA for astrophysics applications. The study identified 6 key findings, summarized below:

1. ISA has emerged as a viable approach for observatory assembly, with key capabilities demonstrated in space over the last decade. Engineering development needs and technology gaps for specific observatory designs will have to be addressed.
2. ISA removes the constraint of fitting the entire observatory in a single, specific launch vehicle by enabling the use of multiple launchers.
3. The ISA approach is scalable and can enable observatory sizes that cannot be achieved by conventional, single-launch approaches.
4. ISA offers an in-situ approach to servicing the observatory and replacing the instruments by re-using the on-board robotics needed to assemble the observatory in space. No additional servicing infrastructure is required.
5. ISA changes the risk posture of observatory development and makes it potentially more manageable. Hence, ISA may be a preferred implementation approach compared to conventional single-launch approaches for observatories, particularly those with 10m class or larger apertures.

6. ISA may offer opportunities for reducing the costs of conventional, single-launch observatories for aperture sizes 15m or less, particularly when including the servicing infrastructure in the mission.

The study also identified two capabilities that are key to enabling ISA which are currently at a maturity insufficient to support ISA and designated as having low readiness for ISA. The first being modularization of the observatory and development of interface requirements between the modular elements used to assemble the system, and the second being the ability to perform in-space verification and validation. For both of these capabilities, the flight demonstration and active development program examples identified are the Hubble Space Telescope, instruments on the International Space Station, and the James Webb Space Telescope. In addition, some of the driving engineering and technological challenges that will need to be overcome to mature those capabilities and enable ISA are discussed. Of those, the most relevant to the SDC study are:

- The ability to assemble modules to form precise, linear, stable trusses
- Multi-agent collaboration and autonomous assembly
- Attitude control with a moving center of mass during assembly
- Precise joining interfaces for robotic assembly (and servicing)

ISA also presents a challenge for cost estimation, as traditional cost modeling is primarily dependent on mass and draws from historic databases of missions and instruments that are subject to constraints not relevant for ISA, e.g. single launch compatibility. The iSAT study concluded that ISA is fundamentally different than traditional mission implementations and existing cost models are inadequate for purposes of estimating costs for missions utilizing ISA. Instead, a more grassroots approach is necessary and included in the iSAT study. The study indicates that ISA can be competitive with a traditional approach for telescope apertures starting in the 5-10 meter range, but given the uncertainties in the cost estimation however, the study concludes that the cost estimates for an ISA and a traditional implementation are within the uncertainty bounds.

While ISA does present benefits to an SDC mission, given the maturity of the key capabilities necessary to enable ISA, and the uncertainties associated with cost modeling approaches and estimation, ISA is not currently a likely candidate for SDC implementation. However, if the key engineering and technology developments discussed can be matured in parallel with the SDC study, ISA could become a more favorable option in the future.

Action (Langley, Chris Edwards): Create a white paper outlining the cost of in-space assembly solutions. The paper should highlight the maximum aperture size improvements this technique could offer over traditional deployed apertures as well as the cost associated with this benefit.

Non-NASA Radar Technology Capabilities

The increasing presence of commercial and international spaceborne SAR systems makes it inefficient to consider the SDC mission in isolation. Though SAR systems are built to serve the different purposes of their customers, opportunities for collaborations that provide mutual benefit are always possible. The technology workshop focused on two possible scenarios for such coordination. The first was on partnerships where NASA and an external partner both contribute physical assets to the completion of a mission, while the second addressed the scenario where NASA simply purchases data from an existing system without having any stake in the system itself.

Several radar experts participated in the session from three different commercial companies who might have a potential interest in collaborating with SDC, though each collaboration would be of a different nature. Simon Lee from Stanford Research Institute (SRI) has been involved with the development of a smallsat SAR system funded via the NASA ESTO program. Jayanti Sharma with MacDonald, Dettwiler, and Associates (MDA) has a long history with building radar systems for the Canadian government including the still operational Radarsat 2 and the Radarsat Constellation Mission (RCM) launched shortly after this workshop on June 12th. Finally, Christian Roemer and Peter Gath from Airbus have been involved with the ROSE-L concept study currently under formulation with the European Space Agency (ESA) and gave an overview of the current plans for that mission.

The CubeSat Imaging Radar for Earth Science (CIRES) is an instrument from SRI that is being primarily funded by NASA ESTO's Instrument Incubator Program (IIP). The radar leverages electronics miniaturization to fit on resource constrained platforms like CubeSats although not necessarily exclusively for CubeSats. The instrument was designed to perform interferometric measurements up to altitudes of 500 km although the specific needs and goals of SDC were not part of the current design considerations. The instrument operates at S-band and has a proposed size of 42x22x22 cm^3 with the membrane antenna in a stowed configuration. The design is not for a specific spacecraft bus at the moment and currently sits at TRL 4 having had several prototypes built for airborne demonstrations. These prototypes have gradually reduced the size of the instrument first from the bed of a truck, then to a small Cessna airplane, and most recently to an even smaller unmanned aerial vehicle. These demonstrations have shown sample images taken during flight but the exact performance metrics in a space configuration at 500 km altitude is not known at this time.

The critical question for the SDC team to evaluate is whether or not the present development of such an instrument might save NASA resources toward developing a small constellation of radars that would achieve SDC goals. In this regard, while the CIRES instrument itself will not fulfill SDC objectives, the technology behind the miniaturization efforts could be very applicable and helpful to the program. CIRES has focused on electronics miniaturization as the primary development motivation, and while the development is still ongoing, the focus to be the smallest may distract from SDC goals of minimizing repeat-pass times with global coverage. The 5 m^2 antenna proposed is in line with SDC minimum requirements for achieving necessary interferometry performance in the absence of radiometric requirements, and the antenna design is similar to other waveguide-fed concepts . Concerns remain about the proposed configuration concept in terms of its ability to maintain pointing and also thermal management within a mission concept that would transmit for nearly one half of every orbit. These concerns could be allayed by allowing the spacecraft bus to increase from a CubeSat form factor while maintaining the electronics specifications to a smallsat. In all, the CIRES development provides a good benchmark for what is possible for SWaP minimization in radar electronics and the instrument can provide a good baseline for an architecture study utilizing many small satellites.

The Radarsat Constellation Mission represents another type of possible collaboration. RCM consists of three smaller SAR satellites, with the option to increase to six at a later date, that operate equally spaced around a sun-synchronous orbit. With a maximum swath width of 500 km at 100 m resolution and nearly 200 km at 5 m resolution, the system has the ability to collect repeat-pass interferometry at 4 day intervals. These specifications look very much like what SDC is attempting to do, but there are also some significant differences. First, the system operates at C-band. While the faster repeat rates might reduce the impact of temporal decorrelation, SDC still prefers the performance and canopy-penetration capability of L-band or S-band systems to make up the majority of its data needs. RCM is also more limited in its data collection capability than NISAR, with each satellite only capable of collecting data for fifteen minutes per orbit. Thus, the three RCM satellites combined collect approximately the same coverage per orbit as the single NISAR satellite. In order for this configuration be beneficial to SDC, which wants to double or triple the coverage of NISAR, the cost of each of the smaller satellites must be 6x to 9x less expensive than NISAR. Evaluating this trade-off will be a core part of our architecture assessment. Finally, the data model for RCM is under the control of the Canadian government and is not planned for free and open release, while SDC will require the free and open release of low level data products.

Despite those differences in objectives, MDA, the company that built the RCM satellites has built up considerable experience from the design of RCM, and believes modifications to the base design could deliver the space segment of a mission architecture for SDC at lower cost than development from the ground up. Such a savings sound logical in principle, but the experience of many on the SDC team has been to the contrary. The common opinion among many on our panel has been that changes of any significance to a complex design such as a spacecraft tend to ripple throughout the system such that the cost savings relative to a new design effort are illusory. Nevertheless, leveraging the experience of commercial organizations can be beneficial and should be properly evaluated as part of the acquisition strategy. But the SDC team does not believe the selection of a mission architecture should be weighted toward a pre-existing architecture in the hopes of significant cost savings for the mission.

Finding: Several platforms exist that could serve as a starting point for an SDC instrument. However, careful evaluation must take place to weigh any significant deviations such as frequency band, aperture size, or airborne use that may involve significant cost changes that ripple through the entire system.

The ROSE-L mission concept is a candidate mission for ESA's Copernicus program. Like other elements of Copernicus, if selected, ROSE-L will have a thirty year commitment for data continuity from ESA. The concept consists of two L-band SAR instruments operating at opposite ends of a sun synchronous orbit with 12-day repeat, in essence offering two components of deformation every six days. The mission shares significant overlap in science objectives with SDC including monitoring subsidence, polar ice sheets, and sea ice extent. As currently proposed, each spacecraft should achieve 260 km swath width with 50 m resolution cells with good radiometric performance. Like the Sentinel-1 constellation, which is also a Copernicus element, the data from ROSE-L would most likely be free and open. In many ways, the mission concept is comparable to flying two instruments with NISAR-like capabilities and a long-term commitment to data continuity. Based on the description from Airbus presented at the workshop, it is possible that this system would be capable of meeting SDC objectives on its own if operated to do so.

A proposed mission with such common goals must surely have some common ground for mutual benefit. The SDC architecture study team sees several ways in which international collaboration might occur. The current mission concept is restricted to a Vega-C launch vehicle that is constraining antenna size. NASA may be able to provide a larger launch vehicle that would help relieve those constraints. NASA could build additional NISAR-lite style spacecraft of similar specification to the ROSE-L instruments in order to augment the overall constellation offering even shorter repeat times down to four or even three days. NASA could also choose to augment the two satellite constellation of ROSE-L by providing co-flyer satellites that would provide additional value, such as multi-squint observations for 3D deformation vectors and atmospheric removal as described in the section on observation geometries. There are quite a few technical possibilities. The challenge for SDC would be to find common ground with ESA, who have already formulated a standalone mission concept, in a manner that provides mutual benefit but does not have any potential to compromise their baseline mission to which they are committed. In terms of cost though, such a partnership may be the only way to achieve the SDC mission objectives within the cost guidelines that NASA has provided in the decadal survey.

Recommendation: The ROSE-L mission concept is very close to the needs of SDC and is proposed in a similar time frame to SDC needs. The architecture team should open channels of communication for possible collaboration options and ways that NASA might augment or further enable this mission as one architecture possibility.

Commercial Data Availability

An alternative approach to leveraging the spaceborne SAR community would be to work within the operating models of existing SAR systems to either use freely or purchase their data for SDC purposes. Rather than collaborating with other organizations to piece together a complete mission architecture as discussed in the last section, this approach would simply seek to acquire data. In all likelihood this process would be used to augment another SDC data collection system rather than completely achieve SDC goals.

The canonical example of such a process is the example set by the addition of Sentinel data to the NISAR program of record. Sentinel-1 is a C-band SAR constellation that is part of ESA's Copernicus program, and offers SAR data in a free and open manner. The original mission concept for NISAR required the spacecraft to yaw flip between both left-looking and right-looking configurations to eliminate coverage holes in the polar regions. This concept forced NISAR to exchange continuous time series of data for complete global coverage. NISAR has been able to obtain an agreement from ESA to collect regular data over the north pole, thereby meeting the global coverage requirement, while also allowing NISAR to remain left-looking throughout the mission, giving a continuous time-series of data collected in that orientation. This type of collaboration between two independent SAR missions is a first and perhaps shows the way for future collaborations.

Representatives from several of the leading SAR systems in operation joined the SDC team to discuss how to pursue such a collaboration. Jayanti Sharma from MDA who also participated in the panel on radar hardware collaboration represented the Radarsat-2 data model, which differs from the data model that will be followed by the RCM mission. Radarsat-2 followed a public-private partnership model between the Canadian government and MDA where the CSA funded the development of the system, while MDA operates and sells data from the instrument. RCM, on the other hand, was built by MDA for the CSA who operates and controls the data. Luca Pietranera represented E-GEOS, who operates the COSMO-SkyMed (CSM) constellation. CSM was developed by ASI, the Italian space agency, and also follows the public-private partnership model. John Collins from Airbus represented the TerraSAR-X (TSX) family of satellites. This includes both the TerraSAR-X and TanDEM-X satellites commissioned by DLR, the German space agency, and PAZ, commissioned by the Spanish space agency. Matti Ekdahl from Iceye and Joerg Hermann from Capella Space represented the new purely commercial alternative to this business model. Rather than a design sponsored by a government agency and procured through an established prime contractor, these companies are commercial startups producing a design they see fitting a market need, with development risks borne by the investors. Finally, Col. Steve Butow from the Defense Innovation Unit has a unique vantage point for all of these SAR developments with a mandate to foster commercial development and purchase available SAR data for the benefit of the U.S. government.

SDC is mandated to provide its data free of charge and open to the public, which is a significant challenge to working with the various business models of these systems. The open data policy of Sentinel and NISAR is a very recent development within the past few years. While NASA does not object to paying for data to augment SDC, it will want that data to be made freely available to become part of the program of record. Despite the seeming contradiction, there are a range of possible options. While NASA has not specifically defined what free and open means, Gerald Bawden, the SDC program manager from NASA Headquarters, clarified that it must include single-look radar imagery, and not only higher level data products such as interferograms or lower resolution multi-looked imagery. One possible approach may be to agree to purchase specific data sets over sensitive agreed upon areas such as fast moving glacier grounding lines in order to augment the sampling of time-series estimates, if the companies could agree to allow the free release of that data and factor that into the purchase price. Another method might be to allow free release of purchased data after a specified waiting period, as the commercial value of the data increases exponentially as it approaches real-time. These are simply examples to highlight how such arrangements might be possible. The SDC study team goal was not to define specific mechanisms for data purchase but rather to find common ground for where such arrangements might be useful.

Most SAR systems in operation today are focused on fast revisit of key areas rather than global background monitoring. Those at X-band (TSX, CSM, Iceye, Capella) favor high resolution imagery. Aside from those common features though, each system offers different abilities. TSX has specialized in cross-track interferometry for the generation of digital elevation maps, but has also demonstrated repeat-pass change detection capabilities related to infrastructure monitoring. CSM offers deep genetic stack time series of data with data collection focused on population centers. Radarsat-2 has a specialty tracking shipping in the northern latitudes, but has a long history of data continuity at C-band with image stacks over 100 deep over many areas of the globe. For the commercial start-ups, Iceye and Capella, data latency and reliability are core capabilities that they hope to bring to the market within the next year or two. These capabilities seem to be best aligned with assisting SDC in its goals for applications space. The ability to respond quickly with information on damage areas in the event of large natural disasters can be critically important to first responders. NASA has fostered this capability through the ARIA program, and NISAR will have operational procedures to handle these situations. Many in NASA would like to see that objective continue or even expand with SDC. Augmenting these capabilities with commercial data, perhaps at a higher resolution than an SDC baseline system could provide would be a worthwhile investment.

> **Recommendation: Commercial data seems best suited to meeting the applications goals of SDC, particularly for disaster response or geohazards needs. Develop a scenario where commercial data purchases are used to provide low latency responses to event-driven applications on top of a background collection system for science.**

We also see possible uses for data purchase in cryosphere science and should explore possible data purchases in that area.

Recommendation: Commercial X-band data can provide valuable augmentation for cryosphere science. The architecture study team should explore data purchases for this purpose, particularly for COSMO-SkyMed, the TerraSAR family of satellites, and Iceye constellation that is already offering data for purchase. Additional systems should be considered as their data becomes available for investigation.

Interpreting the future of SAR constellations at the proposed time of SDC launch, including SDC itself, is very much like reading tea leaves. Each of the panelists represented have a program in the works for a future SAR mission. Airbus is pursuing the HRWS concept as a follow on to the TSX series. CSM has a next generation system planned to launch within the next year, while RCM launched shortly after this workshop. Iceye and Capella are both at the early stages of deploying their constellations. Given this uncertainty, it is difficult to tell what will come to fruition. SDC will therefore take the approach to evaluate what is useful based on the currently available or near-term available data as the architecture plan is developed. It is assumed that a similar capability will be in place when SDC launches in order to avoid extrapolations on future capabilities that may not materialize. This assessment may evolve as time goes on.

Appendix A: References

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Appendix B: Workshop Agenda

Day 1: Space Segment Technologies, Monday, May 20th

8:00 AM Introduction (Paul Rosen)

8:15 AM Headquarters Perspective (Gerald Bawden)

8:30 AM ESTO and the Designated Observables (Bob Bauer)

8:45 AM SDC Science Definition Process (Ala Khazendar)

9:00 AM SDC Objectives and Discussion Framework (Stephen Horst)

9:30 AM Networking Break

9:45 AM Spacecraft Bus Session

A discussion of the suitability of commercial spacecraft buses in support of NASA directed missions of various sizes.

PARTICIPANTS

Brad Hirasuna, Aerospace Corp. (moderator)

Tim Flora, Sierra Nevada Corp.

Ruben Rohrschneider, Ball Aerospace

Austin Williams, Tyvak

11:00 AM Networking Break

11:15 AM Antenna Technologies Session

Discussing the state of various antenna technologies and their suitability to meet SDC aperture needs across various platform sizes.

PARTICIPANTS

Richard Hodges, JPL (moderator)

Gregg Freebury, Tendeg

Todd Pett, Ball Aerospace

Yahya Rahmat-Samii, UCLA

Sembiam Rengarajan, CSUN

Mark Thompson, NGC Astro

12:30 PM Lunch Break

1:30 PM Special Topic: Hyper-Integration (Arbi Karapetian)

Reducing size, weight, and power by leveraging multiple functionality from spacecraft components.

2:00 PM Networking Break

2:15 PM Thermal Technologies Session

A discussion of thermal technologies that can help get orbital duty cycles to cover most land and coastal areas while also preserving reasonable size and mass of the spacecraft

PARTICIPANTS

Perry Knollenberg, NGC (moderator)

Raul Polit-Casillas, JPL

Baratunde Cola, Carbice

Ben Furst, JPL

3:15 PM Networking Break

3:30 PM On-Board Processing Session

A discussion of the road map for on-board processing technologies, the need for low-latency identification and classification within the applications for SDC, and the ability to apply a COTS reliability mentality to non-mission critical electronics.

PARTICIPANTS

Ernie Chuang, JPL (moderator)

Steve McClure, JPL

David Hawkins, JPL

Michael Lowry, ARC

Adrian Tang, JPL/UCLA

Day 2: Mission Systems Technologies, Tuesday, May 21st

8:00 AM Industry Instrument Capabilities Session

Discussing SAR instrument capabilities that could meet SDC goals outside of the NASA umbrella.

PARTICIPANTS

Stephen Horst, JPL (moderator)

Simon Lee, SRI

Jayanti Sharma, MDA

9:30 AM Networking Break

9:45 AM Commercial Data Opportunities Session

A discussion about the possibilities for collaborating with commercial SAR data providers and how those data rights might fit within NASA's free and open data policy

PARTICIPANTS

Stephen Horst, JPL (moderator)

Col. Steve Butow, DIU

John Collins, Airbus

Matti Ekdahl, Iceye

Joerg Hermann, Capella Space

Luca Pietranera, E-GEOS

Jayanti Sharma, MDA

10:45 AM Networking Break

11:00 AM Telecom and Ground Station Session

A discussion of the ground system and improvements needed to handle not only SDC but all of the other high data volume missions proposed for the same time frame.

PARTICIPANTS

Jared Stallings, JPL (moderator)

Eric Harris, NASA NEN

Sean McDaniel, ATLAS

Chris Boody, AWS

Katherine Monson, KSAT

Ron Faith, RBC Signals

12:20 PM Lunch Break

1:20 PM Special Topic: Options for Access to Space (Jason Jagdmann)

A discussion of the parameters to consider when getting a constellation to space.

1:50 PM Networking Break

2:00 PM Formation and Observation Strategies Session

Discussing the potential for unconventional approaches to the observation strategies from unique measurement approaches to in-space assembly technologies.

PARTICIPANTS

Razi Ahmed, JPL (moderator)

Todd Faulkner, ENSCO

Brian Hawkins, JPL

Thiemo Knigge, Airbus

Ryan Mccormmick, JPL

Cinzia Zuffada, JPL

3:15 PM Networking Break

3:30 PM SAR Data and Analytics Session

A discussion of the NASA data lake and how to enable an ecosystem that allows applications within SDC goals and beyond to flourish.

PARTICIPANTS

Piyush Agram, JPL (moderator)

Matt Calef, Descartes Labs

Derek Edinger, Ursa Space

Hook Hua, JPL

Xin Li, Orbital Insight

Dan Pilone, Element84