2014 NISAR Applications Workshop: Linking Mission Goals to Societal Benefit

October 28-29, 2014

Workshop Report

0. Executive Summary

The NASA-ISRO SAR (NISAR) Project conducted its first annual community Applications Workshop on October 28-29, 2014 and sought input from the broad end user community to identify potential science and societal needs that are not currently captured in the mission formulation plan. NISAR, which is planned for launch in 2020, would deliver global time-series of polarimetric radar imagery with 12-day sampling and a repeating orbit that would enable repeat-pass interferometry over the life of the mission. The goals of the workshop were to a) inform the applications and end user communities about the mission; b) to solicit feedback on mission design elements; c) to explore new applications research directions; d) identify high-value products; and e) search for collaborative opportunities. There were 149 participants at the workshop, and 38 people who participated remotely through Webex and teleconference. The workshop audience represented a broad range of science applications, research communities, and government agencies.

Invited presentations highlighted potential applied science areas with SAR, both currently considered mature and those possibly advanced by the mission. These applications areas included natural hazard and infrastructure monitoring, disaster response, forests and wetlands, agriculture and land use, oceans and sea ice, and water-related applications. Breakout sessions discussed applications community observational needs and data product specifications in greater detail, and how these needs could be met with observations, collection modes, fundamental SAR imaging and derived products.

There were three broad findings from the workshop that will inform the integration of NISAR into NASA's applications program and NISAR data into the community:

1. There is a significant base of user groups positioned to take full advantage of NISAR products. In particular, mission agencies for natural hazard response and ocean monitoring have the capabilities now to exploit NISAR data to improve existing services. High impact, mature applications include:
    a. geologic hazards: Earthquake, volcano, subsidence, and landslide monitoring
    b. disaster response: damage and hazard assessments from earthquake displacements; oil spill mapping
    c. forests and wetlands: mapping and monitoring of hydro periods; carbon monitoring through the United Nations Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) program.
    d. agriculture and land use: crop area monitoring
    e. oceans and sea ice: high-resolution marine wind speed and wave spectra analysis, sea-ice tracking, ship-lane monitoring, oil spill detection and classification
    f. hydrology: ground-water subsidence monitoring

2. There is an equally significant base of potential users who, given increased understanding and awareness of SAR in general and NISAR in particular, could build expertise, and begin application development to exploit NISAR data. Promising, high impact, applications include:
   a. Infrastructure monitoring: sink-holes, levees, dams and embankment, bridge, and road surface/pavement assessments
   b. disaster response: damage detection; flood extent mapping
   c. forests and wetlands: soil moisture monitoring; forest recovery and succession
   d. agriculture and land use: soil moisture monitoring; yield/biomass; risk from disease and drought
   e. oceans and sea ice: shoreline mapping; severe storm parameters
   f. hydrology: soil moisture monitoring; snow-water equivalent; permafrost monitoring
3. Latency is a critical issue for operational agencies using SAR data. NISAR currently carries a requirement of 5 hours latency once the data has been collected for urgent response capability but shorter latency and more routine availability were recognized to be of considerable value for disaster response and other near real-time applications.

The following recommendations were made relative to these findings:

1. Keep established user groups informed of and engaged in product development through annual workshops to maximize the utility of NISAR data products for mature applications.
2. Establish a NASA Applied Science Program initiative – possibly in coordination with other agencies – that (1) fosters education efforts that highlight the value of SAR, InSAR, PolSAR, and time-series analysis for NISAR's main application communities, (2) promotes the rapid development of new products, and (3) promotes the adoption of products and methods akin to the SMAP early adopters program. This initiative would establish a connection between the science products that will be delivered by the NISAR project to the NASA Data Access and Archiving Centers (DAACs) and the user community as a whole.
3. To address the latency issue, the applications community requests the NASA Applied Sciences program to investigate what it would take to guarantee low latency for the mission, including possible partnerships with other agencies or commercial endeavors. The workshop participants understand that additional requirements lead to additional cost, but feel strongly that the value of the NISAR mission will be tremendously enhanced if some of these requirements were met.

In addition to the above broad findings, workshop participants from a range of disciplines expressed great interest in the potential of NISAR's S-band instrument for their applications. This workshop focused only on the NASA component of the mission science requirements –

namely the L-band instrument. Many participants recommended the development of a more specific utilization plan for S-band, either jointly or as a stand-alone capability in future application workshops. In fulfillment of developing the S-band utilization plan, the participants recognized that joint airborne campaigns using L-band and S-band radar instruments could be beneficial.

1. Overview

1.1 The NISAR mission

Since the 2007 National Academy of Science "Decadal Survey" report "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" [Committee on Earth Science, 2007]. NASA has been studying concepts for a Synthetic Aperture Radar (SAR) mission to determine Earth change in three disciplines – ecosystems, solid earth, and cryospheric sciences. NASA has now partnered with the Indian Space Research Organisation (ISRO) to formulate this mission [Rosen et. al, 2013]. The NASA-ISRO SAR (NISAR) mission would expand on previous NASA concepts that exploited an L-band array-fed reflector SAR configuration to enable > 200 km swath at full SAR resolution and full polarimetry [Rosen et al., 2015], necessary to meet the requirements in all three disciplines. As the partnership concept with ISRO developed, it became clear that flying dual L- and S-band SAR capabilities, with L-band electronics supplied by NASA and S-band electronics contributed by ISRO, would satisfy science and application requirements of the U.S. and India. A dual-frequency fully-polarimetric SAR with the potential for global coverage every 12 days would offer unprecedented capability that researchers could exploit in new and exciting ways.

NASA and ISRO both have great interest in a range of global science objectives relating to the cryosphere, ecosystems, and the solid Earth. These objectives would be primarily addressed with the L-band radar system, which is being designed for a high on-orbit duty cycle. In addition, ISRO has a number of applications areas that drive their motivation for adding an S-band capability to the spacecraft, primary among these being agricultural biomass estimation, but also snow and glacier studies in the Himalayas, coastal winds and bathymetry, coastal processes, and hazard monitoring. The general science requirements described in Table 1 drive specific system capabilities such as measurement resolution and measurement accuracy, which vary depending on the science target. Science and applications potential can be enhanced or extended with the addition of repeat-pass polarimetric S-band interferometry.

The NISAR partnership between NASA and ISRO would expand on previous collaborations on ISRO's Chandrayan-1 lunar and Mangalyaan Mars missions, and on NASA's QuikSCAT and ISRO's OCEANSAT Earth observation missions. NISAR would be the first collaborative project where both the technical and programmatic contributions are balanced at the mission level, with major hardware contributions contributed by both organizations,. See Appendix 8 for a summary of the overall mission characteristics. Further information on the science and implementation of NISAR can be found at the mission website (http://nisar.jpl.nasa.gov).

Table 1. NISAR Mission Science & Application elements and their associated requirements

Science or Application Element	Requirements
Ecosystems [3,4] · Biomass Disturbance · Agriculture · Wetlands and Coasts · Alpine Vegetation · Soil Moisture	 · Global, seasonal estimates of disturbance and regrowth · Regional crop yield estimates surrounding growing seasons · Regional seasonal estimates of inundation and mangroves · Focus on seasonal characteristics of Himalayan ecosystems · Regional soil moisture surrounding growing seasons
Deformation · Earthquake/Volcanic Cycle Deformation · Land Subsidence, Landslides	 · Weekly vector sampling of deformation processes on land in plate boundary zones and volcanic hotspots globally · Biannual mapping of global land masses for intraplate events · Regional weekly sampling of high-priority aquifers, subsurface reservoirs, and incipient or anticipated landslides
Cryosphere · Ice Sheet and Shelf Dynamics · Sea Ice Dynamics · Sea Ice Thickness · Mountain Snow/Glacier Dynamics · Permafrost and Freeze/Thaw	 · Weekly vector sampling of deformation processes of ice sheets in winter to capture inter-annual variability · Semi-weekly sampling of deformation of Arctic and Antarctic sea ice · Explore potential for sea ice thickness estimation · Weekly vector sampling of deformation processes of mountain glaciers to capture inter-annual variability · Explore the potential of quantifying permafrost variability and freeze/thaw transition
Ocean Processes · Bathymetry · Wave Spectra · Coastal Winds	 · Bathymetry in India's coastal waters · Ocean wave spectra in India's coastal waters · High-resolution coastal winds in India's waters
Other Disasters · E.g. Tropical Cyclones, Tsunamis, Floods, Oil Slicks, Fires	 · As natural and anthropogenic disasters unfold, direct observation resources and accelerate dissemination of data to users

1.3 Application related NISAR capabilities

The overarching purpose of the NASA Applied Sciences Program is to discover and demonstrate innovative uses and practical benefits of NASA Earth science data, scientific knowledge, and technology. One of the Applied Sciences Program's strategic goals is to coordinate with NASA flight missions like NISAR to support applications as well as science goals, starting with mission planning and extending through the mission life cycle. For more information, please visit http://www.nasa.gov/applied-sciences/about.html.

The 2014 NISAR Applications workshop facilitated communication between the key stakeholder communities by bringing together members of the NISAR Science Definition Team, NISAR project team, ISRO, along with the academic research community, applications community, industry, and other federal, state, and international agencies.

Predominantly, the observation strategy and operational concept for NISAR are crafted to meet the main science requirements listed in Table 1 and have not yet been optimized to also address the diverse science application needs. The mission does have a requirement for urgent response, with 24-hour turnaround on retargeting and 5-hour latency. This rapid response requirement is part of the mission, as the Science Definition Team recognized the great utility NISAR data would have for disaster response if the data could be made available quickly. Observations from NISAR would include deformation from repeat pass interferometry that could characterize earthquakes, volcanic deformation, sinkhole collapses and other catastrophic events that cause displacement at the surface. In addition, SAR can characterize changes in ground conditions that enable damage detection and flood monitoring, without the clear sky and daylight limitations of optical imagery. NISAR's polarimetric L-band capability over the full swath would enable better crop type, crop health, forest ecology and wetlands monitoring than has been possible to date.

The mission design enables systematic repeat coverage of most of the Earth's land and ice masses – this is a critical characteristic for applications where reliable coverage is needed over areas that may be outside of most scientific study regions (e.g., monitoring for changes in infrastructure). NISAR's global land and ice collection plan is in contrast to many of the current SAR mission observation plans that collect data only over specific regions that have been requested or approved for particular studies: many SAR satellite collection strategies lack a 'background' mission for acquiring data elsewhere. NISAR's 12 day repeat cycle, with ascending and descending coverage on each orbit cycle would provide dense sampling in time, as well as reliable spatial coverage. Another important design feature of the NISAR mission is NASA's open data policy, allowing everyone in both the scientific and applications community free and open access to all of the NISAR data products. This open data policy enables a larger group of researchers to develop uses for NISAR, and also enables resource-limited end users access to the same high quality data.

1.4 The 2014 NISAR Applications Workshop

The goals of the applications workshop were to a) inform the applications and end user communities about the mission; b) solicit feedback on mission design elements; c) explore new applications research directions; d) identify high-value products; and e) search for collaborative opportunities. In this workshop, the broad science applications and research communities, governmental agencies, developers, and potential users of data were invited and engaged in discussions to ensure the mission produces data and products that are of most value to the applications community.

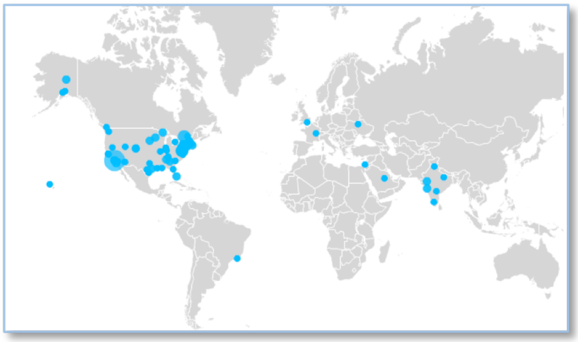

Figure 2. Blue markers show home cities of participants (both in person and remote) at the workshop. Marker size is proportional to the number of participants at that locale.

Invited presentations highlighted potential applied science areas with SAR, both currently considered mature and those possibly advanced by the mission. These applications areas included geologic hazard and infrastructure monitoring, disaster response, forests and wetlands, agriculture and land use, oceans and sea ice, and water-related applications. Breakout sessions discussed the observational needs of the applications community and addressed data product specifications in greater detail. Following each breakout, session leaders reported the results of their breakouts to the full workshop audience in a plenary session. At the end of the first day, an interagency panel was held, featuring representatives from federal agencies with interest in the mission as well as representatives from NASA and the NISAR project. At the end of the workshop, there was a summary session, where the cross cutting results and recommendations of the workshop were discussed. The complete agenda for the workshop can be found in Appendix 6.1.

There were 149 participants at the workshop, and 38 people who participated remotely through Webex and teleconference. Figures 2 and 3 give a breakdown of the geographic distribution of attendees, as well as which communities they represented. The complete list of attendees is given

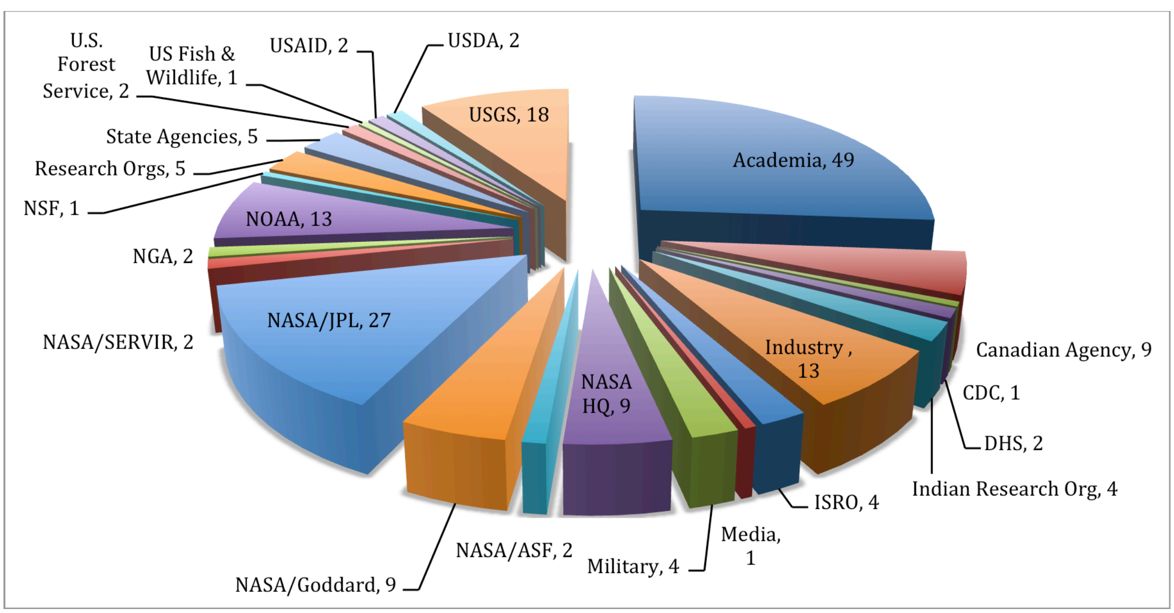

Figure 3. Breakdown of the NISAR Applications Workshop attendance by self-identified association.

in Appendix 6.2.

2. Cross Cutting Findings and Recommendations

Five overarching findings/recommendations were formulated for NISAR-related applications, common across all or most of the application focus areas. These were discussed in the plenary session at the end of the workshop and are summarized in the following list:

The NISAR mission as planned is well suited for a wide array of applications.

The current design and observation plan for the NISAR mission (see Appendix 8 for details) will meet the needs of many in the applications community, across each focus area. Representatives of several application disciplines noted that they already use SAR data from other missions in their every-day operations. Hence, there are already a significant number of end-user systems that are ready to use NISAR data if the mission were launched tomorrow.

There is interest from the applications community for exploring the capabilities of S-band data.

There was an interest in exploring NISAR's ISRO-provided S-band SAR capability, particularly in combination with L-band. Prior to the NISAR launch in 2020, airborne measurements from S-band SAR instruments would help the applications community to fully explore the potential of S-band data. An S-band 'utilization' plan was also recommended; this would establish prioritized observation sites with high potential for enhancing applications products with S-band.

Latency is a critical issue for many operational agencies using SAR data.

In the current mission design, NISAR would regularly provide image products with 30-day latency, with a capability of delivering basic products within 5 hours after collection for urgent response. Some operational agencies must provide products rapidly after acquisition for urgent response and for routine product generation. Others have monthly reporting requirements that would need data products in under the planned 30-day latency. While NISAR is not an operational mission, the value of its data for urgent response and for many operational or experimentally operational applications would be greatly enhanced with shorter latency for both urgent response and routine product delivery. Workshop attendees recommended that NASA explore the impacts of operating NISAR more like an operational mission, especially with lower latency for routine products in certain areas that already benefit from operational characteristics of the international SAR constellation. It is recognized that additional capability would require additional resources.

An education program to raise the radar literacy within the U.S. is needed.

An education program in the years leading up to the NISAR launch would be a worthwhile investment for NASA to increase the science and applications value of the mission.

Representatives from several federal agencies acknowledged that they do not currently have the in-house expertise to take full advantage of products they can envision from NISAR. The form that an education program would take needs to be discussed, but could include short courses and webinars, visiting research programs, and tutorials for different user communities.

End-users would benefit from more data products that distill essential and critical information.

End users generally need a higher level of information reduction in their products than is available from commonly used SAR products found in the scientific community. Development of end-user oriented products that 'take the radar out' would greatly broaden the applications value of the NISAR mission. Definition of these products would involve experts in SAR and groups of end users willing to invest in technical discussions of how best to extract important information and uncertainty values. Commercial companies that provide value added products for end users should be able to contribute in this arena.

3. Application Focus Area Summaries

The workshop breakout sessions were divided into 6 application focus areas, with discussion sessions led by members of the NISAR Science Definition Team and others in the NISAR science and applications community (see agenda in Appendix 6.2 for list of breakout session leaders). The discussion topics varied depending on the issues that were important for the particular application focus area and the experience base of the participants in their group. The summaries are limited to the inputs of participants, do not attempt to be comprehensive, and therefore may miss some perspectives. Each chapter follows roughly the same format – introduction, summary tables, detailed discussion, and recommendations – but the content varies depending on the emphasis in the topic areas in each group.

Workshop participants were asked to identify the highest maturity applications using SAR data, and the applications where SAR data have the highest impact on the efficacy of the application. Each group took a different approach to this effort, and the tables and descriptions below are an attempt to summarize these in a uniform fashion.

In addition, participants were asked to construct an Applications Traceability Matrix that provides details of measurement requirements and the maturity levels of various applications. Links to these matrices, which are maintained on the NISAR web site as living spreadsheets that will be updated as applications and our understanding of the image matures, are in the Appendix 7.

3.1 Forests & Wetlands

Author: Josef Kellndorfer

Forests are a key natural renewable resource providing a range of ecosystem services like carbon sequestration, natural habitats for a biodiverse fauna and flora, storage and filtering of water resources, and providing food, fiber, and biofuel for human consumption. Intact forest ecosystems are important means to control the spread of disease, and deforestation has even been linked to public health epidemics like the 2014 Ebola outbreak in Western Africa. The United Nations Framework Convention on Climate Change (UNFCCC) has recognized the reduction of greenhouse gas emissions from deforestation and forest degradation while safeguarding biodiversity and societal needs to live in and use forests (REDD+), as significant means to counteract climatic disruption. Under the agreements, sound information on forest extent and its associated carbon stock and flux is crucial for the monitoring, reporting, and verification (MRV) of REDD+ type policy formulation and enactment.

Furthermore, timely, accurate, and quick turnaround information on our global forest ecosystems is essential for silvicultural management and decision support, protection, and restoration of forests. Some core information needs are: 1) regular mapping and monitoring of forest extent in natural and managed forest landscapes, 2) identification of cause and areas of disturbance, e.g. from logging, insect, fire, flooding, wind throw, 3) estimation of aboveground biomass or growing stock volume, and 4) estimation of stand canopy height, often used as a proxy for biodiversity and input to biomass estimation models. While operational identification and rapid monitoring of disturbance events at coarse resolution (250-500 m) with optical sensors has proven invaluable, regular observations with higher resolution sensors provide some key benefits in tracking landscape-scale functional restoration as a sum of small-scale events. Forest disturbance often occurs at small scale and thus is difficult to track with coarse sensors. Hence, below-hectare-scale monitoring with medium-resolution sensors in a timely fashion is crucial.

Similar to forests, globally distributed wetlands are a key natural resource providing a range of ecosystems services from constituting key biological habitat areas, to supporting human livelihoods in the food chain of fisheries, agricultural irrigation, and drinking water storage. Many wetland ecosystems are in duress from increases in weather extremes, such as increases in droughts or torrential rain induced land erosion and subsequent wetland sediment contamination.

Another vulnerable zone of climate warming feedbacks where both forest and wetland ecosystems are rapidly changing, are the boreal and subarctic permafrost regions. There, significant moisture regime changes in the freeze-thaw patterns lead to dramatic changes in soil drainage, seasonal vegetation greening and browning, drought and fire cycles, as well as increasing carbon release from thawing ancient permafrost soils. Human management of the high latitudes is challenged with the need to understand these changes of the natural landscapes, and its impact to the ecosystem services that are affected by high-latitude land use and management.

Associated with degradation of our ecosystems is the increasing global spread of invasive species. Declining forest and wetland ecosystem health is often rooted in anthropogenic introduction of invasive species and their spreading in favorable shifts in the climate regime. Agricultural pests can also be linked to changes in soil moisture patterns.

The following tables provide a summary view of the anticipated forest and wetland applications for NISAR from two perspectives: (1) maturity of the application and potential impact of NISAR data on the efficacy of the application; and (2) technical feasibility of NISAR observation plan for supporting the application.

Maturity and Impact Applications Matrix

Maturity / Efficacy of NISAR data	Higher Maturity	Lower Maturity
Major Impact	- Wetland Hydro-Period - Aboveground Biomass/Carbon Monitoring	- Wetland water level change - Soil Moisture
Substantial Impact	- Wetlands Classification - Silviculture management	- Forest Recovery and Succession

Technical Feasibility Table

Adequacy of NISAR baseline plan to meet application requirements					
Characteristic / Application	Coverage	Freq/Pol Modes	Resolution	Latency	Comments
Wetland Hydro-period	Great	Adequate	Great	Adequate	For some applications, would want < 5 days latency
Carbon Monitoring	Great	Adequate	Great	Adequate	
Wetlands Classification	Great	Great	Great	Great	Addition of global S-band would improve classification accuracy
Silvicultural management	Great	Great	Great	Great	S-band useful
Wetland water level change	Great	Adequate	Great	Great	
Soil Moisture	Great	Great	Great	Great	
Forest Recovery and Succession	Great	Great	Great	Great	

Opportunity with SAR

A core benefit of spaceborne SAR data is its active remote sensing capability in cloud-covered conditions independent of solar-illumination. Since abundance of vegetation is strongly correlated with abundance of rainwater availability, clouds are a major impediment to high-resolution optical remote sensing at high temporal repeat. This is an invaluable strength of SAR imaging, also with respect to the possibility of measuring at day-night or high-latitude seasonal light conditions. High temporal and spatial resolution SAR observations thus complement optical instruments for a range of aspects of key forest and wetland monitoring needs. SAR observations at longer wavelengths (L- and P-Band) have proven particularly useful for forest monitoring as the longer wavelength show biomass and growing stock volume sensitivity. SAR is inherently sensitive to changes in two core target variables: moisture and structure. Atmospheric conditions (clouds, smoke and other aerosols) are largely negligible in SAR remote sensing, in particular at longer wavelengths. Thus, time series of SAR observations are inherently an observation of temporal moisture patterns (soil and plant moisture, flooding, freeze/thaw conditions) or changes in surface structure (soil roughness, vegetation structure changes e.g. from phenology, deforestation or forest disturbance). The NISAR mission with its global 12 day repeat orbit at dual-frequency polarimetric L-band and S-band coverage (regionally over India and select other study sites) will provide an unprecedented wealth of global SAR time-series data which will be invaluable in gaining scientific insight into ecosystem dynamics and provide a sound database for applications in forest and wetland monitoring and management.

Core Forest and Wetlands Applications potential for NISAR

During the Fall 2014 NISAR Application workshop the following areas were identified as mature and influential application opportunities for observations with the NISAR mission.

Mature and influential

NISAR will augment and significantly enhance the series of international L-band SAR missions as part of an international L-band constellation (ALOS, ALOS-2, SAOCOM-1a/b). With NASA’s open data policy as a means to global access to the dense observation time-series, NISAR can make significant contributions to many application domains, foremost the need of annual carbon accounting for REDD+ MRV in tropical regions where cloud cover prevents optical remote sensing from continuous observation. Also, vegetation height (> 100 Mg/ha biomass) and biomass mapping (for regions < 100 Mg/ha), will provide refined baselines for emissions estimates in the accounting framework of carbon treaties. The accurate and timely NISAR measurements of deforested and disturbed forest cover will also be invaluable.

Mapping and monitoring of wetland hydro-period is deemed a mature application for SAR with its sensitivity to soil moisture and seasonal flooding extents. Examples of uses of SAR data are the assessment of the effectiveness of wetland restoration, improved modeling and monitoring of disease vectors spreads and wetland health; modeling of wetland bio-geochemistry through refined small-scale water table measurements which has impact on methane emissions in particular in tropical and boreal environments. An improved spatio-temporal resolution provides means to refined characterization of biological habitat conditions, a core need for agencies like the US Fish and Wildlife, National Park Service, Bureau of Land Management, and state governments. Improved scales in seasonal flood and moisture mapping will provide a better planning basis for investing in new infrastructure, e.g. cattle watering holes, dams. Also associated with wetland hydro-period measurements are potential benefits to defense mapping needs, e.g. for the planning of deployments along coastlines, or the improved modeling of water quality (e.g. mercury and nutrients) through improved understanding of refresh rates from flooding and draining in the wetland systems.

Mature

The monitoring of silviculture management and decision support will be a mature application that will benefit from NISAR. Examples are the mapping of managed forests, e.g., in identifying conversion of primary forest to agroforest like palm oil, rapid assessment of fire hazards, and disease monitoring leading to wood degradation. The NISAR data will support decisions on restoration priorities, treatment priorities, assessment of ecosystem services, e.g. from improved understanding of water level changes in riparian buffer zones, and disease outbreak models.

Also, improvements are anticipated in the classification of wetlands and peatlands into current and historic wetlands where moisture patterns are often pronounced in the SAR data. This is highly relevant to modeling agricultural pests and infectious diseases as well as modeling spread of invasive species.

Influential

It is anticipated that forest recovery and succession models can be improved with NISAR's dense time series of SAR observations at regional to global scale which will lead to an improved understanding of approaches for landscape-scale functional restoration of forests and forested wetlands. This understanding will thus lead to increases in the ability to monitor forest productivity and tree growth. A core application for NISAR will be the improvements in fire risk modeling from improved soil moisture data and drought tracking at fine scale as well as monitoring of active fires as part of constellation of global SAR missions that could be combined to provide rapid daily maps of fire activity and damage. InSAR technology applied to measurements in wetland water level change monitoring will likely lead to improvements. Overall, improved soil moisture monitoring has significant application potential in the general monitoring of drought and flood patterns, which has linkages to agricultural applications like irrigation, crop disease vectors and assessing variations in post-disturbance regrowth.

End-Users Communities

The US Forest Service, US Fish and Wildlife, National Park Service, Bureau of Land Management, NOAA, USGS, US Department of Agriculture, Food and Agriculture Organization of the United Nations, and state, county, and municipal governments are expected to be among the key end-users for the SAR applications described above. The applications traceability matrix for Forests and Wetlands (see Appendix 7) has a breakdown of end user communities by application.

Recommendations

The assembled group reached the following recommendations for SAR data products and their latency:

1. Availability of S-Band data would significantly improve soil moisture models and crown biomass estimates and should be added to the NISAR observation plan.
2. In general, radiometrically terrain-corrected, fully-georeferenced, GIS-ready, SAR imagery should be made available for ease of ingestion in existing GIS and Decision Support Systems.
3. Terrain correction should be applied with the best DEM source available.
4. Raw data should be available as well, as some agencies might prefer a processing chain tailored to their existing ancillary data (e.g. better lidar DEM for a state) than available to the NISAR project during mission data processing.
5. Time-series stacks should be processed to the highest standard of speckle noise reduction, e.g. via multi-temporal filtering approaches.
6. Full-resolution products are preferred to lower-resolution products, as area estimates will benefit from refined delineation.
7. Developing a plan for rapid delivery of data products tracking illegal logging would be very useful for law enforcement, particularly in cloud cover conditions in the core areas of illegal logging. The plan would include, among other things, calibration needs and latency requirements.

3.2 Agriculture & Land Use

Author: Paul Siqueira

Approximately 1.5 billion hectares, 10% of the Earth's land surface, is dedicated to the practice of agriculture, with an additional 3.2 billion hectares used for pasture [Monfreda et al., 2008]. Because of the critical nature of food resources to national security and international crisis management, statistics are kept on agriculture production worldwide, with crop-assessment efforts spanning domains from very local to international levels, as food products are grown and brought to consumers. The timeliness of such assessments is a key component in the provision of information that helps national and international agencies, as well as markets, direct resources necessary for maintaining the continuity and providing for the delivery of food supplies. Because of the large variation of farming practices and crop-types worldwide, the application of remote sensing for agriculture, to date, has been primarily used for identifying spatial patterns and extent of agricultural land areas, and less so for direct assessments of crop health and production. The combination of remote sensing (optical and radar) with localized resources (e.g. such as can be provided by the USDA) through data fusion is an important resource that continues to be developed and provides significant added value compared to either one of these sources taken by itself.

Recent efforts to increase the use and accuracy of remote sensing data for agriculture applications have been led by the Group on Earth Observations (GEO) under the GEOGLAM initiative (GEO Global Agricultural Monitoring). This initiative consists of governmental and non-governmental organizations that use such data for allocating resources and projecting agricultural outlook, often on a month-to-month basis. These data are used for publishing market projections, allocating resources, and assessing food security. While current remote sensing inputs for crop-area identification methods rely primarily on reflectance spectra from optical data, radar provides a unique set of observations that are insensitive to cloud cover and lighting conditions and primarily sensitive to the structure of ground-cover and the moisture conditions of the ground and crop.

The highest impact of NISAR observations for agriculture can be summarized as

1. making available timely and predictable observations taken every twelve days at high resolution (~10 m) throughout the growing season,
2. a set of remote sensing observations that are primarily sensitive to soil moisture and the structural characteristics of the land cover,
3. observations, that when combined with ancillary data sets, such as optical observations, weather data, and farmland inventories, can be used for estimating crop health and yield production.

The tables below provide a summary view of the anticipated agriculture and land use applications for NISAR from two perspectives: (1) maturity of the application and potential impact of NISAR data on the efficacy of the application; and (2) technical feasibility of NISAR observation plan for supporting the application.

Maturity and Impact Applications Matrix

Maturity / Efficacy of NISAR data	Higher Maturity	Lower Maturity
Major Impact	- Crop Area - Growth Stage/Phenology/Calendar	- Soil Moisture - Crop Yield/Biomass
Substantial Impact		- Risk (Disease/Drought) -Crop Type

Technical Feasibility Table

Adequacy of NISAR baseline plan to meet application requirements					
Characteristic / Application	Coverage	Freq/Pol Modes	Resolution	Latency	Comments
Crop Area Crop Type	Great	Adequate	Great	Deficient	30 day latency does not meet monthly reporting requirements
Growth Stage/Phenology/ Calendar	Great	Adequate	Great	Deficient	Weekly or more frequent temporal sampling ideal. Need 3 days latency
Soil Moisture	Great	Great	Great	Deficient	Several day temporal sampling ideal. Need 3 days latency
Yield/Biomass	Great	Great	Great	Great	
Risk (Disease/Drought)	Great	Adequate	Great	Adequate	

With the availability of NISAR observations, global assessments of active agricultural crop area on a seasonal (3 month) basis will be enabled, as will more focused assessments of crop type, growth stage and phenology. This latter set of capabilities will be made possible through the development of new algorithms that rely on the repeated and consistent coverage of agriculture regions and correlation of these observations with seasonal ground surveys and crop statistics that are used for national and international reporting.

Once established, and with the observations listed above, the NISAR mission would enable

1. the measure of global crop area to better than 80% accuracy on a quarterly basis
2. the collection of fully-polarimetric SAR data over the principal US and Indian agricultural regions, which can be used for estimating crop type and growth stage, and
3. repeated L-band radar backscatter measures which, when be combined with SMAP and additional resources, will be capable for high-spatial and temporal resolution soil moisture estimates.

The algorithms for providing the quantitative and classification estimates listed above are in different stages of development and complexity. While there are a number of established methods for the determination of crop area, the use of remote sensing for classification of crop type and growth stage are still an area of active research. Such algorithms are often demonstrated at local levels, but are challenging to generalize to scales appropriate for unsupervised classifications that encompass large nations and climate regions. In these cases, the greater challenge is to identify ancillary sources of information that can be depended upon and augment the radar data for improving estimate accuracy.

End User Communities

The US Department of Agriculture (and similar agencies for other countries), the USGS, and the agribusiness community are expected to be among the key end-users for the SAR applications described above.

Recommendations

The following recommendations have been established during the workshop to make observations from the NISAR mission more useful for agricultural applications:

1. Establish an early-adopter program that uses simulated and collected data for algorithm development and to establish data formats and pathways that can be easily ingested into national and international agriculture assessments.
2. Create low-latency (maximum 3 days) path for NISAR data to transition from raw SAR observations to usable products that can be ingested in agency-based agriculture assessments that are typically published on a monthly basis.
3. Continue algorithm development over large geographic areas for the agricultural applications of greatest interest for NISAR. These are:
    1. total crop area
    2. crop-type classification
    3. determination of growth stage
    4. provision of high-resolution soil moisture estimates

3.3 Water Resources, Hydrology, & Subsurface reservoirs

Authors: Tom Farr, Brian Conway, Howard Zebker

Application areas that are most mature are groundwater, surface water, and snow. High-impact applications that are less mature include soil moisture, permafrost and snow water equivalent.

The following tables provide a summary view of the anticipated water-related applications for NISAR from two perspectives: (1) maturity of the application and potential impact of NISAR data on the efficacy of the application; and (2) technical feasibility of NISAR observation plan for supporting the application.

Maturity and Impact Applications Matrix

Maturity / Efficacy of NISAR data	Higher Maturity	Lower Maturity
Major Impact	- Groundwater monitoring	- Soil Moisture - Permafrost
Substantial Impact	- Snow - Surface water	- Snow Water Equivalent

Technical Feasibility Table

Adequacy of NISAR baseline plan to meet application requirements					
Characteristic / Application	Coverage	Freq/Pol Modes	Resolution	Latency	Comments
Groundwater monitoring	Great	Great	Great	Great	
Soil Moisture	Great	Great	Great	Adequate	
Snow	Great	Great	Great	Great	
Snow Water Equivalent	Great	Great	Great	Great	
Permafrost	Adequate	Great	Great	Adequate	Reduced culling could improve coverage

Groundwater applications of NISAR are focused on the repeat-pass interferometric technique to map and monitor ground surface subsidence and rebound at the cm level. This provides an indirect indication of the state of aquifer systems as groundwater is pumped out and is naturally or artificially recharged. The most mature application is the direct ability to map the surface extent of land subsidence above pumped aquifers, the identification of subsurface groundwater barriers, and the linking of changing subsidence patterns based on dynamic pumping approaches.

Changes in the subsidence patterns from seasonal to annual subsidence indicate possible over-pumping: record-low and long-term subsidence implies irreversible compaction of the aquifer system and partial loss of groundwater storage capacity. Quantitative inference of groundwater storage changes requires more research.

Early detection of new areas of potential flooding and infrastructure damage may be aided by the ability to map and track subsidence. Areas of low topographic relief are susceptible to flooding, and subsidence can create new areas prone to flooding that would be undetected until a major flood occurs. In addition to elevation changes, deformation induced changes in surface slope can seriously alter and even reverse surface water flows with associated erosional and flood hazard.

Infrastructure damage is usually more obvious as roads, bridges, and aqueducts crack, but subsidence maps can quickly delineate the problem areas, helping point the way toward remediation.

The main user communities for subsidence mapping and monitoring are state and federal water resource agencies. Currently, the California Department of Water Resources (CA DWR) and the Arizona Department of Water Resources (AZ DWR) have projects in place for mapping and monitoring subsidence. Other western US states are considering this as well. Other agencies responsible for flood-hazard mapping would be interested, including the CA DWR's Central Valley Floodplain Evaluation and Delineation Program, the US Army Corps of Engineers, and the US Bureau of Reclamation. Agencies responsible for maintenance of highways and aqueducts may be interested in these products as well and are also described in the Hazard and Infrastructure Monitoring chapter. An example is the interest of engineers designing the CA High-Speed Rail in InSAR subsidence maps because the planned route passes through areas of known subsidence.

It is important to note that not all groundwater basins produce surface deformation when groundwater is pumped; alluvial basins such as California's Central Valley are the types of aquifer systems that produce subsidence when pumped because of the presence of fine-grained layers ("aquitards"). Also of note is the fact that NISAR will join a long history of radar satellites with the interferometric capability. These satellites have monitored many hydrologic basins since the early 1990's making the derivation of long time series of surface changes possible. This enhances the interpretation of groundwater movement, which can be very slow.

Soil Moisture is a land-surface parameter of great interest in a wide array of research and applications. The moisture content of soils down to about 10 cm is a secondary effect (after surface roughness) on the strength of radar scattering from a surface. The wavelength and polarization of the radar wave also affects the interpretation making NISAR, with its dual-wavelength and multi-polarization modes, a unique asset. The quantitative measurement of soil moisture from SAR observations is not as mature as some other applications described here, but has advanced greatly in the last few years and should experience a quantum jump with the launch in early 2015 of the Soil Moisture Active-Passive (SMAP) mission, which will use radar and passive microwave sensors to map soil moisture globally. Those measurements will be at a few km resolution, but should constitute a basis for future application of NISAR observations to mapping of soil moisture.

The community of users of soil moisture maps would have a wide range from individual farmers, agricultural agencies, to weather and climate prediction agencies. More information can be found on these applications at the SMAP home page: http://smap.jpl.nasa.gov.

Surface Water applications include many aspects, some of which overlap into other application areas. Most straightforward is the mapping of surface-water extent, which includes flood mapping, coastal inundation caused by floods and tidal fluctuations, wetland mapping, and lake and ocean shoreline changes. Water surfaces reflect radar energy away from the sensor so appear dark and easy to map. In addition, water surfaces covered by overhanging vegetation appear very bright due to multiple reflections and scattering between the water surface and vegetation. Thus floods obscured by vegetation can also be mapped.

Another application that is less mature is monitoring of surface-water level with the interferometric technique, but that may benefit from the launch in 2020 of the Surface Water and Ocean Topography (SWOT) mission, a single-pass interferometric radar capable of high-resolution and precise topographic measurements.

Many state and federal agencies are concerned with surface water extent mapping and monitoring. Water resource agencies discussed above as well as the US Geological Survey (USGS) monitor surface water, most notably with a national network of stream gages and lakes level gages. Agencies responsible for hazard mitigation and response also rely on in situ and satellite imagery to assess flooding. Environmental agencies are particularly interested in mapping and monitoring wetlands (see Chapter 3.1 for more detail on wetlands monitoring). Ocean and coastal-related agencies are concerned with coastal inundation and coastline changes (see Chapter 3.4 for coastal applications).

Snow also has mature applications for NISAR as well as very important applications that await further research. Like surface water extent, snow cover extent is a straight-forward application that is very important for water resource management. Particularly in higher latitudes, where it's dark much of the winter, radar images may provide the only reliable maps of snow extent. Another relatively straight-forward application of NISAR radar imaging is the detection of the start of snow-melt. Just as radar images are sensitive to liquid water in soils, the transition from frozen to liquid water in snow can show up clearly, particularly in a time series of radar images obtained around the time of melt initiation. Again, this information is important for water resource managers, especially in the more arid western US where snow provides a large fraction of total water resources.

While snow cover extent is important, even more important is a quantitative measure of snow depth or volume and the actual water content of the snow (Snow Water Equivalent, or SWE). These last two applications are the subject of much ongoing research and would be a boon to water resource managers throughout the western US and many other arid regions of the world. Research indicates that longer wavelength radar may penetrate further into the snow pack, so may provide deeper information. However, both wavelengths of NISAR may serve to decrease ambiguities. Multiple polarizations will probably be necessary as well.

Water resource agencies in the western US are keenly interested in measurements of SWE for planning reservoir operations and other surface-water allocations. The CA DWR has been funding airborne campaigns using lidar and multi-spectral imaging to help determine SWE on an experimental basis. An orbital technique would be more efficient, and could be coupled with the airborne observations for Cal/Val.

End User Communities

State water resource agencies, NOAA, and the USGS are expected to be among the key end-users for the SAR applications described above.

Recommendations

For optimal use of NISAR data for water-related applications, the breakout group at the workshop agreed on the following recommendations for the proposed NISAR mission:

1. In order to advance the maturity level of less mature algorithms, we recommend working towards making data available from similar radar sensors (e.g., PALSAR 1&2, Sentinel-1, and the upcoming SAOCOM missions), and to choose a few test sites for extensive and intensive data collections and possible field campaigns.
2. Provide software training and support on radar software for interferometric and polarimetric processing.
3. Develop a hydrology Cal/Val working group that could support the project.
4. Provide low latency data products for hazard-related hydrology applications like flood mapping and infrastructure monitoring that require fast turn-around.
5. Develop a plan and evaluate feasibility for reducing culling in high latitudes to support some applications that would benefit from acquisition of all NISAR passes:
    a. Monitoring of coastal changes in Alaska during 1 or 2 months of rapid change.
    b. Seasonal ice break-up on frozen rivers.
    c. Snow-melt detection in spring.

3.4 Oceans, Sea ice, Coastal Zones

Authors: Frank Monaldo, Bill Pichel, Ben Holt, Pablo Clemente-Colón

In the process of acquiring data for its primary missions, we anticipate that NISAR data will be useful for monitoring the oceans and coastal zones as well aiding the operational monitoring of high-resolution changes in the sea ice.

The following tables provide a summary view of the anticipated oceans, sea ice, and coastal zones applications for NISAR from two perspectives: (1) maturity of the application and potential impact of NISAR data on the efficacy of the application; and (2) technical feasibility of NISAR observation plan for supporting the application.

Maturity and Impact Applications Matrix

Maturity / Efficacy of NISAR data	Higher Maturity	Lower Maturity
Major Impact	- Sea Ice Mapping - Oil Mask - Marine Wave Spectra - Hard Target Detection	- Shoreline Mapping - Severe Storms
Substantial Impact	- Marine Wind Speed	

High Maturity Applications

There are three SAR applications being regularly used in an operational day-to-day context: sea-ice detection and classification, SAR-derived wind speeds, and oil detection and mapping. Other applications have been demonstrated in applications demonstrations, and/or research case studies. The following applications are viewed as the most mature.

1. Sea Ice

The U.S. National Ice Center (NIC) and the Canadian Ice Service (CIS) have been using SAR imagery since ERS-1 in the 1990s to monitor sea ice. This effort has continued with the intervening SAR satellites. Currently, Radarsat-2 data are the primary source of SAR data in the Polar Regions. Although the process of detection and classification has not been automated, human analysts are producing operational products at the NIC and other ice services around the world as an aid to navigation. The ice centers will use the high volume of Sentinel-1 SAR data as it becomes available to test automation of the process in anticipation of NISAR and related missions.

For sea ice, a resolution of 100 m resolution is a threshold, with finer resolution a plus. For NISAR, three hour raw data delivery latency is a threshold goal with 1-2 hours an objective. Currently at the NIC, 6-12 hour latency is the requirement; however, by the NISAR era a more stringent latency requirement is projected as SAR data becomes useful in sea-ice modeling assimilation.

Technical Feasibility Table

Adequacy of NISAR baseline plan to meet application requirements					
Characteristic / Application	Coverage	Freq/Pol Modes	Resolution	Latency	Comments
Sea Ice	Great	Great	Great	Deficient	Need 3 hour or better latency for raw data delivery, and it must be operational, not just urgent response
Marine Wind Speed	Deficient	Great	Great	Deficient	1 dB calibration needed, similar latency requirements as for sea-ice
Marine Wave Spectra	Deficient	Great	Great	Deficient	No plan for this mode or product for NISAR. Need 4-hour operational latency of raw data delivery
Hard Target Detection	Adequate	Adequate	Great	Deficient	
Oil Mask	Adequate	Great	Great	Adequate	
Shoreline Mapping	Great	Great	Great	Great	
Severe Storms	Deficient	Great	Great	Deficient	See marine wind speeds for deficiencies

The current baseline plan uses a single VV mode for sea ice coverage. The availability of co-pol and cross-pol imagery together would improve sea ice retrievals, particularly in the automation of algorithms. Also, the availability of both L-band and S-band data will provide improved first year/multi-year ice discrimination, particularly in warmer months.

2. Marine wind speed

SAR winds have been routinely used to estimate wind speeds since Radarsat-1 in the late 1990s. In May 2013, NOAA began producing SAR winds as an operational product using Radarsat-2 data. Wind speed accuracies of better than 2 m/s are regularly achieved. Operations will be extended as Sentinel-1 data come online. Although wind speed products are mature at C-band, L-band measurements have also been made. It is anticipated that after a modest period of calibration, L-band winds will be operationally useful. A resolution of 100 m is finer than necessary. The key to usefulness will be well-calibrated and stable observations with a latency minimized to 1-2 hours.

SAR wind retrieval requires calibrated normalized radar cross-section (NRCS) imagery. At this point, no specific error analysis has been performed for L-band, but we anticipate that 1 dB calibration accuracy (or at least stability) will be necessary for L-band wind speed retrieval.

Operational winds are currently computed using either HH or VV like-pol imagery. Recent work has suggested that cross-pol imagery might prove useful in SAR wind speed retrieval at high wind speeds, such as in hurricanes or extra-tropical storms. Marine wind direction is highly desirable but has proven problematic under numerous ocean conditions.

3. Marine wave spectra

SAR wave spectra have been measured since the days of Seasat. SAR imagery is particularly useful in estimating wavelength and direction, with wave direction being a unique satellite observation only available from a SAR system. Although wave spectra products are mature, they are not currently produced in an operational context in the U.S. NOAA plans to make such products available before the launch of NISAR utilizing Sentinel-1 data. ESA will also provide wave spectra measurements from the Wave Mode (i.e. small images taken periodically over the ocean portion of each pass) of Sentinel-1.

A resolution of 25 m or better is required and the 10 m resolution of NISAR will be even better. The imagery need not be absolutely calibrated, but needs to be linear in NRCS.

4. Hard Target Detection

During the availability of Radarsat-1, SAR imagery was regularly used for ship and iceberg detection. There are a variety of hard target detection algorithms, though they are all focused on detecting bright objects above the background noise with a given probability of error. Ship and iceberg detection improves with resolution. Useful ship detection schemes in particular have been shown to operate well at 25 m resolution but higher resolution permits the detection of smaller objects.

While ship and iceberg detection can be performed with co-polarization, cross-pol is generally preferred for hard target detection due to the low ocean-background NRCS at cross-pol. Availability of fully polarimetric data permits the use of improved retrieval algorithms. A latency of at most 3 hours is necessary, with 1-2 hours preferred and within ½ hour is optimum for enforcement.

5. Oil Mask Estimation

Although there is on-going and successful research on automatic oil mask estimation from SAR imagery, at this point analysts are still in the loop. The Satellite Applications Branch of NOAA uses available SAR imagery and human analysts to measure surface oil extent. This application is currently limited by availability of data. However, when abundant SAR data are available, as was the case during the Deepwater Horizon spill in 2010, these data are invaluable for mapping oil under most cloud, weather, and solar illumination conditions

A resolution of 50 m is adequate, and co-polarization preferred. Although a latency of 6-hours is useful, a latency of 1-2 hours is preferred (with half an hour preferred for enforcement).

Impactful Applications

The working group identified two applications as "impactful." These are being actively researched and promise to be of good practical value in the near future. These are shoreline mapping and severe storm parameters.

6. Shoreline Mapping

The extraction of waterline information from SAR imagery, particularly multi-polarization SAR data is a current topic of research. The capability to determine coastline changes over long time periods for determining the effects of sea-level changes and the rapid determination of short-term coastline changes due to severe storms and tsunamis are important applications of shoreline mapping with SAR.

7. Severe Storm Parameters

Another important emerging application of SAR imagery and topic of current research is the measurement of hurricane/severe storm parameters. High-resolution measurements with SAR of eye location/shape, rain-band location, characteristics of roll vortices, swell wave parameters, and wind-speed variations provide some unique information about hurricanes and other severe storms that have the potential to improve forecasts of hurricane track and intensity.

The Applications Traceability Matrix (see Appendix 7) provides details of measurement requirements and the maturity levels of various applications. However, in this applications area there are three recurring issues that may impact NISAR mission design: coverage, latency, and acquisition mode.

Mission Design Considerations

Coverage

NISAR is designed to cover the Earth's land areas and Arctic regions. The benefits of NISAR to ocean and coastal zone applications depend critically on the amount of data over the marine environment. Very simply put: no ocean data - no ocean applications.

Fortunately, as NISAR passes are planned to begin and end over the water, they will already image over coastal areas and inland waters extending approximately 50-100 km from the coast. To the extent to which such passes can be expanded to begin earlier and end later over the ocean, NISAR data will prove to be increasingly useful for ocean applications.

As a first priority, to support operational coastal ocean applications, we would recommend extending passes into the US coastal areas covering the Exclusive Economic Zone (EEZ), typically 200 nautical miles (370 km) offshore or about 1 additional minute of acquisition time. Longer passes over water and over other global coastal regions augment the value of the measurements.

Latency

Maximum value for coastal ocean and sea-ice applications measurements occurs when there is a minimum latency between acquisition time and data availability to weather forecasters and sea-ice analysts. Although data with long latency can be of value for retrospective analysis and research and would not be ignored, to meet the needs of operational agencies, we would recommend decreasing the data latency as much as possible.

For ocean wind, wave, and current measurements, data latency of less than 3 hours is recommended, with 1 hour being an optimal goal. At 6 hours, the value to forecasters drops precipitously. Currently sea-ice measurement latency requirements fall within the 6-12 hour range. However, as ice monitoring facilities such as the US National Ice Center move to predictive sea-ice models, by the time NISAR is launched, latencies on the order of 3 hours may be optimal.

Modes of operation

Fortunately, all the modes of operation are consistent with ocean wind and wave measurements. Because the background land mission will typically operate at HH/HV, this will be the most common mode at the ocean/land boundary. There is no need to switch modes. The 10-m resolution is more than adequate for ocean wind and wave measurement applications. While ship detection is possible at 10-m resolution, this application will always benefit from finer resolution. Although we have no experience with S-band data, there is a general consensus that either L-band or S-band data could be used for ocean applications as long as they are well calibrated and stable. For some applications, having simultaneous L and S band will likely improve application products; however, this is a topic for research, initially requiring only limited dual-band data takes for research purposes.

End-User Communties

NOAA, including the Natonal Ice Center, is the key end-user for the SAR applications described above. The International Ice Patrol is another potential end-user for sea-ice related products.

Recommendations

The breakout group at the workshop agreed on the following recommendations for the optimal use of SAR data for ocean applications using the proposed NISAR mission:

1. Extend passes out over the ocean to cover at least the U.S. EEZ, farther offshore if possible.
2. Decrease data latency as much as possible - 3 hours is recommended with 1 hour being an optimal goal.
3. Enable access to simultaneous L- and S- band data over the ocean as much as possible, as it is useful for research, and eventually for improved products and algorithms.
4. Collect simultaneous co-pol and cross-pol data as much as possible, as it will allow use of improved algorithms.
5. Work towards a calibration accuracy of 1 dB or better for accurate wind speeds.

3.5 Disaster Response & Recovery

Authors: Matt Pritchard, Tim Stough, Sang-Ho Yun

The all-weather, day/night capability of SAR imagery can be essential for observing the ground immediately after a disaster occurs -- disasters are often obscured by clouds (e.g., floods, volcanic eruptions, and fires) that SAR is able to "see through." SAR is also a versatile tool that can be used in at least five different ways to detect disaster-induced changes to the ground [e.g., Pritchard & Yun, 2015]. All of these methods require at least two radar images acquired at different times in order to determine the change between them. Thus, an image is needed "before" the disaster to compare with "after." In this respect, NISAR's regular, frequent observations will be an improvement relative to other missions – this will provide a short time interval between "before" and "after" images, minimizing sources of error in determining surface change caused by the disaster.

The tables below provide a summary view of the anticipated disaster response and recovery applications for NISAR from two perspectives: (1) maturity of the application and potential impact of NISAR data on the efficacy of the application; and (2) technical feasibility of NISAR observation plan for supporting the application.

Maturity and Impact Applications Matrix

Maturity / Efficacy of NISAR data	Higher Maturity	Lower Maturity
Major Impact	- Volcanic Eruptions - Earthquake Characterization	- Damage Detection
Substantial Impact	- Oil Spills	- Floods

Technical Feasibility Table

Characteristic / Application	Coverage	Freq/Pol Modes	Resolution	Latency
Volcanic Eruptions	Great	Great	Great	Adequate
Earthquake Characterization	Great	Great	Adequate	Adequate
Oil Spills	Adequate	Great	Great	Adequate
Damage Detection	Great	Great	Adequate	Adequate
Floods	Great	Great	Great	Adequate

The breakout group identified 30 different NISAR application areas for disaster response and recovery. For many of these applications, pilot studies are underway or complete. One key limitation to developing applications is that there are few available datasets comparable to NISAR (that is, L or S-band data with a 12 day repeat and 30 or more acquisitions per year).

High Maturity Applications

The following three applications areas are viewed as the most mature since SAR data have been demonstrated in real-world disaster response situations, and are used by response agencies when data are available:

1. Volcanic eruptions

SAR data can be used to map the location of ground displacements from magma movement, lava, ash, or lahar deposits and their impact on infrastructure. These maps are already being used operationally by USGS Volcano Observatories and the Volcano Disaster Assistance Program, a USGS program that provides volcano disaster assistance internationally. During the 2006 eruption of Merapi volcano in Indonesia, information provided from SAR about volcano summit activity proved useful for timely evacuation. Using SAR products for volcanic eruptions overlaps with hazard monitoring that occurs at volcanoes that may be restless, but not erupting (see Chapter 3.6). After an eruption, the hazard monitoring begins immediately, looking for observations that will help answer the questions "What will the volcano do next? Is the magma chamber refilling and is another eruption imminent?" Damage detection from changes in SAR reflectance properties (see below) could also be used to map the location of lava, ash, or lahar deposits.

2. Earthquake characterization and permanent displacements

Interferograms spanning an earthquake can directly map the earthquake's location, the surface rupture extent, and amount of fault slip on the surface – information that is important to assess potential damage to buildings and other infrastructure (e.g., the 2002 Denali earthquake fault crossed the Alaska oil pipeline). Interferograms can be used to infer earthquake location and detailed distributions of fault slip in combination with seismic and GPS data to provide the best estimates of ground shaking. These combined calculations have been implemented for a few test cases, including the 2014 Napa earthquake, and then used by the USGS National Earthquake Information Center to estimate the ground shaking (Shakemap), damage and fatalities (PAGER), and infrastructure impact (ShakeCast). While the workflow has been developed and tested to use SAR and GPS data to produce the most accurate maps of earthquake locations and shaking, it is not yet operational.

Earthquake ground displacement including tilt, uplift/subsidence, shearing and their potential impact on infrastructure can be derived almost directly from interferogram products with a few assumptions (e.g., assuming all deformation is vertical). Maps of permanent ground displacement, tilt, and shear strain caused by earthquakes could be useful for focusing resources in the short term to identify which infrastructure (e.g., bridges, pipelines) might be most deformed during the mainshock and susceptible to damage from aftershocks, how tilting might affect flow in canals or water pipes, how subsidence could impact flooding in coastal areas or at levees, etc.

3. Oil spills

SAR can be used to detect and characterize oil emulsions on water. This technique is relatively new and still in development; it potentially needs a system with a noise floor lower than can be achieved from spaceborne SAR; however, spaceborne SAR has a well-known capability to map the extent of the spill, as was demonstrated extensively during the Deepwater Horizon spill in 2010. This application is discussed in greater detail in Chapter 3.4 on ocean-related applications.

Lower Maturity but Potentially Impactful Applications

The working group identified two developing applications that promise to be of "impactful" practical value in the near future. These include use of SAR for damage detection and flood mapping.

4. Damage Detection

Building and infrastructure damage due to earthquakes, tsunamis, tropical cyclones, and tornadoes, as well as ground surface change due to liquefaction, volcanic deposits, and landslides can be mapped using coherence changes between images before and after an event. Radar-based damage mapping is complementary to more traditional damage mapping based on optical data that require daylight and can be obscured by clouds. Change detection based on radar coherence can be done by machine thanks to the controlled similar imaging geometry for repeat-pass interferometry, whereas optical change detection has often been done by manual visual inspection. Thus, SAR observations have great potential to provide rapid damage detection products over large areas following disaster events. The concept has been proven for several events (e.g., 2011 Christchurch earthquake, 2013 Super Typhoon Haiyan) and NISAR's regular and frequent observations will improve the ability to assess changes caused by earthquakes, volcanic eruptions, and wind storms. More study is needed to assess the capabilities and limitations of SAR for reliable damage mapping

5. Flood Extent

The extent of floods can be mapped using the difference in the radar wave scattering properties on dry land and water, and SAR imagery has been demonstrated to be useful for flood mapping. Floods are a common type of disaster that impacts almost all parts of the Earth. They are also frequently associated with cloud cover, so the day-and-night and all-weather capability of SAR could be very useful. On the other hand, the extent of floods often changes rapidly, so daily or sub-daily imaging would be best – such a capability could not be developed solely with NISAR, but a combined approach using NISAR in cooperation with the entire global constellation of SAR missions could be useful to disaster responders. Further work is necessary to enable systematic response to flood events as well as the utility of SAR for urban flood mapping – challenging case due to radar shadow and layover.

The Applications Traceability Matrix (see Appendix 7) provides details of measurement requirements and the maturity levels of various applications. However, in this applications area there are two recurring issues that may impact NISAR mission design: resolution and latency.

Mission Design Considerations

Resolution

The power of imaging radar in general and NISAR in particular is that the change detection can usually occur on a pixel-by-pixel basis across the image, providing high spatial resolution maps (about 10 m/pixel) of changes over large areas spanning 10's to 100's of km. In addition, for most applications, the calculation of change detection is done automatically, with little human intervention, and so can be applied over large regions to thousands of images rapidly after a disaster. For some types of disaster (for example, many landslides), a meter-scale pixel size is needed and this is about an order of magnitude smaller than the routine NISAR background data collection.

Latency

The most salient requirement for the use of NISAR data in disaster response and recovery is very low latency. In the wake of a disaster, the quicker the data products are made available, the more useful they are. While the base data latencies are determined by orbit repeat cycles and the timing of the disaster, data are most critical within the first 72 hours after the onset of a disaster.

End-User Communities

The USGS, state and local emergency management agencies, FEMA, USAID, DoD, the US State Dept., the World Bank, the World Organization of Volcano Observatories (WOVODAT), state and local agencies responsible for infrastructure are the key end-user for the SAR applications described above. The applications traceability matrix (see Appendix 7) has a breakdown of end user communities for several of the applications.

Recommendations

The breakout group at the workshop agreed on the following recommendations for the optimal use of SAR data for disaster response and recovery applications using the proposed NISAR mission:

1. A "near-real time" portal to recently downlinked NISAR data to aid in faster response
2. Limited access to near-real time data, which has not gone through the quality control prior to archiving at the DAAC that can be limited to partners and early adopters.
3. Collecting the highest resolution possible NISAR data immediately after a disaster as well as background images at the highest resolution up to 4 times/year over selected sites (pixel size of about 1 m/pixel).

4. Delivering data products to end-users as quickly as possible in the event of a disaster (within 72 hours).
5. Coordination of international observations and background data collection to meet 72 hour data delivery requirement for disaster response.
6. Increasing access to comparable data – short repeat, numerous observations per year -- to help development of applications.

3.6 Geological Hazard & Infrastructure Monitoring

Authors: Shimon Wdowinski, Andrea Donnellan, Franz Meyer, Maggi Glasscoe

NISAR measures deformation, and disruption of the Earth's surface, and is well suited for use in monitoring geohazards and infrastructure. InSAR, particularly Differential InSAR where topography is removed from an interferometrically derived product to measure surface deformation, has been used for over two decades to study deformation and damage associated with earthquakes and is also regularly used to measure volcanic deformation. More recently, InSAR has been applied to studying the integrity, deformation and damage of levees as well as the risks associated with landslide hazards. InSAR is a promising tool for a wide array of other hazard applications including permafrost and glaciers, transportation, and coastal erosion.

InSAR-based infrastructure monitoring is a relatively new and rapidly growing application area of modern spaceborne SAR data that has gained momentum with the launch of higher-resolution SAR systems in the late 2000s and with the advent of InSAR time-series analysis methods such as PS-InSAR [Ferretti et al., 2000; 2001; Hooper et al., 2004; Adam et al., 2009], SBAS [Berardino et al., 2002; Mora et al., 2002; Lanari et al., 2004], and SqueeSAR [Ferretti et al., 2011]. The main applications interests within the infrastructure monitoring discipline include (1) the monitoring of road pavement conditions through the joint analysis of SAR amplitude, coherence, and phase; (2) the monitoring of bridges and the assessment of road network stability; (3) the analysis of road embankments, levees, aqueducts, and dams; and (4) the detection of incipient geohazards near transportation infrastructure, such as landslides and sinkholes (see section on Non-Tectonic Geologic Hazards for more information on landslide and sinkhole analysis) [Hoppe et al., 2014a]. A wide-area assessment of road surface conditions, embankment stability and bridge health based on time-series InSAR analysis was recently conducted in a collaboration between the Virginia DOT and commercial InSAR vendor TRE [Hoppe et al., 2014b] and led to the discovery of a range of infrastructure-related information. Similar studies have also been conducted for areas in Europe and Asia [Heleno et al, 2011; Yu et al, 2013]. While still a developing market, InSAR-based monitoring of bridges has been demonstrated in a range of recent publications and has led to collaborations between government transportation departments and the SAR science community [Bamler et al., 2009; Fornaro et al., 2013; Fornaro et al., 2012].

NISAR data are expected to provide a significant boost to this application area, as it will provide wide-area, medium- to fine-resolution, SAR data with reliable and frequent temporal sampling to the transportation community for its lifetime. Furthermore, NASA's free-and-open data policy will significantly improve cost-benefit ratios for InSAR-based monitoring techniques, making its application in operational services more attractive.

As with tectonic and non-tectonic geological hazards, InSAR will be used to measure surface movements on and around civil infrastructure with an accuracy of ≤1 cm, 1-2 mm/yr. Most infrastructure-related information will be derived from InSAR time series analyses of stacks of multi-temporal SAR images.

The tables below provide a summary view of the anticipated hazard and infrastructure monitoring applications for NISAR from two perspectives: (1) maturity of the application and potential impact of NISAR data on the efficacy of the application; and (2) technical feasibility of NISAR observation plan for supporting the application.

Maturity and Impact Applications Matrix

Maturity / Efficacy of NISAR data	Higher Maturity	Lower Maturity
Major Impact	- Earthquake hazards - Volcano hazards - Land Subsidence	- Levees, Dams, and Embankment Stability
Substantial Impact	- Landslide hazards	- Sinkhole monitoring - Bridge Monitoring and Road Stability - Road Surface (Pavement) Monitoring

Technical Feasibility Table

Adequacy of NISAR baseline plan to meet application requirements					
Characteristic / Application	Coverage	Freq/Pol Modes	Resolution	Latency	Comments
Earthquakes	Great	Great	Adequate	Deficient*	L-band enables long period measurements
Volcanoes	Great	Great	Great	Deficient*	L-band enables long period measurements
Landslides	Great	Great	Adequate	Deficient*	Lower noise at L-band in vegetated terrains
Land Subsidence	Great	Great	Adequate	Adequate	Lower noise at L-band in vegetated terrains
Sinkholes	Great	Great	Adequate	Adequate	Lower noise at L-band in vegetated terrains
Levees, Dams, and Embankment Stability	Great	Great	Adequate	Deficient*	Persistent Scatterer Techniques
Bridge Monitoring and Road Stability	Great	Great	Adequate	Adequate	Persistent Scatterer Techniques
Road Surface (Pavement) Monitoring	Great	Great	Adequate	Adequate	Persistent Scatterer Techniques

* For monitoring, planned scientific latency of 30 days is insufficient to react to incipient activity. One-day latency would be more appropriate.

High Maturity Applications

As pointed out above, SAR data are already being used in an operational day-to-day manner for the monitoring of earthquakes and volcanoes (tectonic) as well as landslides and subsidence phenomena (non-tectonic).

A systematically operating InSAR mission like NISAR, which samples all phases of the tectonic hazards cycle, can significantly contribute to the analysis and management of earthquake and volcano hazard cycles (Table 1).

Table 1

Hazard Phase	Earthquakes	Volcanoes
Pre-event	Interseismic strain Identifies fault activity and geometry	Dome bulge
Event	Displacement field to calculate stress changes and aftershock potential	Explosive eruptions
Post-event	Velocity and velocity gradient field to estimate stress changes	Lava flows Dome recovery

Non-tectonic geological hazards are surface, or near surface, geological processes mainly governed by gravity that can cause significant damage to human life and/or damage to property. The main non-tectonic hazards are landslides, sinkholes, land subsidence, debris flow, rock falling, and permafrost thaw. Some of these hazards are slow occurring and their damage accumulates over the years (e.g., land subsidence), whereas others tend to cause major damage during a catastrophic failure (landslide and sinkhole). In some cases, catastrophic failure is preceded by slow surface movements that if detected can be served as precursors to the main catastrophic event. Recent InSAR studies of sinkhole activities in Israel and Louisiana showed a slow surface movement days and weeks prior to sinkhole collapse [Nof et al., 2013; Jones and Blom, 2014]. Causes for catastrophic failure can be natural, as heavy rainfall that can trigger landslides or debris flow, or anthropogenic, as massive groundwater extraction that can trigger sinkhole collapse.

The following describes in greater detail the applications presented in the tables above.

1. Earthquake Hazards

Question: What is the probability of a damaging earthquake event in terms of location, size, and mechanism?

Monitoring the continued deformation of earthquake regions with NISAR provides insight into continued stress changes and earthquake potential. Earthquakes pose major hazards on the west coast of the United States, and induced seismicity is causing an increase in seismic hazard in other parts of the country. Earthquake hazards are dependent on where earthquakes may occur, the probability of occurrence, size, and mechanism. Strain accumulates *interseismically* and knowledge of the strain field inferred from NISAR deformation maps will provide insight into the potential location, size, and style of future events. When an event occurs, NISAR could be used to identify areas of damage, described elsewhere in this report, but it could also be used to monitor the *coseismic* displacement field from which stress changes can be calculated. These stress changes can be used to estimate hazards from aftershocks or subsequent large events. *Postseismic* motions occur following earthquakes due to afterslip and relaxation of the Earth's crust.

Needs: Deformation maps, systematic monitoring, coseismic displacements
End User Community: USGS, State Emergency Services, FEMA, local governments, Departments of Transportation

2. Volcano Hazards

Question: What is the location and magnitude of volcanic deformation and what is the potential for a hazardous eruption (lava flow, lahar, ash, gases)? When will hazardous eruption occur?

Volcanoes often deform prior to eruption. Global monitoring of volcanoes can identify potentially active volcanoes and imminent eruptions. When an active volcano or volcanic deformation is identified, more intense monitoring can help identify the magnitude and timing of eruption. Summit deformation during eruptions is very important as it is linked to explosivity (e.g. St Helens bulge, Merapi crater splitting). Measurements with a resolution of 100 m x100 m and 2 mm displacement accuracy, posted every 2 m, is needed for summit observations.

Another high-value application for InSAR would be monitoring the magnitude and location of magmatic deformation surrounding eruptive events or sequences of events that might produce ash, especially if observations could be made in the period before the ash eruptions actually occur. The temporal sampling needed for this application may be shorter than what NISAR can provide at 6-day average sampling and may limit its utility during and immediately after an ash eruption.

Needs: Deformation maps, monitoring summit area during eruption, global systematic monitoring
End User Community: USGS, Global Volcanic Ash Advisory Centers, relevant government agencies dealing with volcano response

3. Landslides

Questions: Where and when will a landslide occur? Will the landslide pose threats to lives, property, and infrastructure? When will a catastrophic slide occur?

Landslides pose major hazard to buildings, local communities and transportation corridors located in mountainous terrain. They can cause severe damage to property and infrastructure and can lead to loss of life. Landslides move with various rates and patterns. Some move slowly and steadily, whereas others are episodic and fast, typically after heavy rain events. InSAR observations are very useful in detecting slow moving landslides as has been demonstrated in various studies of landslides [e.g., Tarchi et al., 2003; Hilley et al., 2004; Colesanti et al., 2006]. InSAR-based maps of landslide motion provide key information for estimating the damage that catastrophic landslide movements can impose on nearby property and infrastructure. In Italy and Canada, two countries that operate their own SAR satellites, InSAR is used routinely to monitor landslides especially along transportation corridors in remote areas (e.g., http://treuropa.com/newsletter/insar-infrastructure/).

Needs: Deformation maps, systematic monitoring
End User Community: USGS, relevant government agencies dealing with landslide monitoring, mitigation, and response

4. Land Subsidence

Questions: Where will subsidence cause damage to property and infrastructure? Does subsidence affect the drainage system? Can urban groundwater use be planned to minimize subsidence damage?

Land subsidence due to intense groundwater extraction is a major human-induced geological hazard that affects buildings and urban infrastructure and results in severe economic consequences for both individuals and local government administrations (see Chapter 3.3 for more on using SAR to measure groundwater extraction). The awareness by local water authorities of subsidence hazards has helped contain subsidence to a few cm/yr in most American cities including Las Vegas, Phoenix, Houston and Los Angeles, and restored groundwater levels in several southwestern US aquifers. However, the situation in other areas is still unresolved, where intense ground water exploitation of the underlying aquifers in urban areas has resulted in high subsidence rates and consequently increasing geological hazards [Osmanoglu et al., 2011; Chaussard et al., 2014]. Fast economic growth in many areas suggests that water demand will continue to increase, which will magnify the subsidence and the related hazard in many urban areas. InSAR is being used operationally for groundwater subsidence measurements in areas where the surface appears stable over time at shorter wavelengths. NISAR will extend and improve these measurements to areas with greater surface variability due to its longer wavelength and regular, frequent, sampling strategy.

Needs: Deformation maps, systematic monitoring
End User Community: Relevant government agencies and water authorities dealing with groundwater monitoring and mitigation

Lower Maturity but Potentially Impactful Applications

The working group identified two developing applications that promise to be of "impactful" practical value in the near future. These include use of InSAR to study sinkholes and to monitor infrastructure such as levees, dams and embankments, aqueducts, bridges and roadway stability, and road surface (pavement).

5. Sinkholes

Questions: Where and when will a sinkhole collapse? Will the sinkhole pose threats to lives, property, and infrastructure?

Sinkholes subsidence and collapse are major geological hazards that can cause severe damage to property and loss of life. In Florida alone, there are hundreds of reported subsidence cases each year. Furthermore, the Florida insurance record for 2006-2010 indicates thousands of annual sinkhole-related claims with a total indemnity of about $200 million per year.

Monitoring sinkholes is a challenging task, because most of the activity occurs in the subsurface. Also sinkhole dimensions are fairly small, from meters to tens of meters, requiring high resolution data. Successful detection of sinkholes by InSAR occurred only recently due to the use of high spatial resolution SAR data (1-3 meters) [Nof et al., 2013; Jones and Blom, 2014]. NISAR, with resolutions in the 5-10 meter range at best, would be able to detect only larger-scale sinkholes.

Needs: Deformation maps, systematic monitoring
End User Community: USGS, relevant government agencies dealing with subsidence monitoring, mitigation, and response

6. Levees, Dams, Aqueducts, and Embankment Stability

Question: Where are levees and embankments unstable, resulting in localized or widespread hazards to population and infrastructure?

Monitoring the stability of levees, dams, and road embankments is important for public and infrastructure safety. Levees and dams are constructed to protect communities and infrastructure from flooding and failure of a levee or a dam will pose substantial safety hazards. Road embankments need to be stable to avoid pavement distress and to assure safety of the traveling public.

There have been several successful studies using SAR for levee monitoring [Bakon et al., 2014; Caro Cuenca et al., 2013; Grenerczy & Wegmueller, 2011; Jones et al., 2014; Mascolo et al., 2014] and InSAR techniques are used more and more by government agencies entrusted with the management of infrastructure (such as the U.S. Department of Transportation). Based on the experience gathered with InSAR techniques so far, the community has found that the InSAR data collection and interpretation lends itself to wide-scale scanning and monitoring at the transportation-corridor level, particularly in areas of very dense transportation infrastructure such as roads, bridges, rail lines, and highway embankments. Wide implementation of InSAR monitoring may therefore yield more comprehensive and integrative asset management and inspection programs, and, by revealing early signs of failure on these critical assets, may be a source of considerable return on investment and mitigation of liability.

Needs: Deformation and change detection maps; ideally, pre-classified information (e.g. into a traffic light scheme: (green='No significant deformation'; yellow='Status uncertain'; red='critical deformation') would be useful
End User Community: US Corp of Engineers, Bureau of Reclamations, Transportation agencies; local FEMA offices; USGS; local infrastructure stakeholder community

7. Bridge Monitoring and Road Network Stability

Questions: Where and when a transportation corridor (roads, railroads, bridges) is damaged or in danger of being damaged/close to failure?

Transportation corridors (roads, railroads, bridges) are fragile infrastructure assets that can be damaged by various geological hazards, such as landslides and sinkholes, as well as construction activity and structural failure. InSAR can be used to detect damaged or failing infrastructure elements, resulting in information that can be used to alert operational agencies to a possible threat to public safety.

Measurements of surface deformation have been shown to correlate well with signs of failing or fatiguing infrastructure on the ground [Bruckno et al., 2013a; Vaghefi et al, 2011; Bruckno et al., 2013b]. Usually, road segments undergoing deformation show degrading road surface quality, signs of settlement or tilt, and generally exhibit increased risks to travelers. From recent studies, it is inferred that medium resolution data may be sufficient to obtain information on road network deformation. While the use of InSAR for bridge monitoring is still found to be challenging, it is still believed that aging, degrading, and/or damaged bridge structures should show deformation behavior unrelated to thermal expansion. Recent studies identified a high potential for InSAR-based bridge monitoring, however they also indicated limitations: It was found that high-resolution SAR data at high temporal sampling rates are necessary to measure and track complex bridge motion through time [Gernhardt et al., 2011; Hoppe et al., 2014-2]. These studies also indicated that specialized processing routines may be necessary to optimize the extraction of bridge information from InSAR.

Needs: Deformation maps (for road network analysis); High-resolution and well-sampled SAR data (for bridge monitoring); development of optimized processing concepts for bridge motion analysis
End User Community: US Department of Transportation, state transportation agencies

8. Road Surface (Pavement) Monitoring

Questions: What is the condition of the road surface and how does pavement condition degrade with time? Which elements of the road network need to be maintained and which do not?

Highway agencies spend most of their funding to maintain the existing road network infrastructure. Accurate and timely data are needed to assess performance and deterioration, identify maintenance and reconstruction needs, and determine financing requirements. Despite the importance of pavement condition measurements, data collection tools currently available to measure road conditions are inefficient and prevent network-level data collection at reasonable speed and costs [NYSDOT, 2010].

Several U.S. DOT-funded studies are currently underway that focus on the potential of InSAR for pavement condition monitoring. In addition to the InSAR phase signal, these studies utilize amplitude and coherence time series for determining pavement condition as well as the change of pavement condition with time [Hoppe et al., 2014a]. Novel processing concepts such as SqueeSAR-type techniques and methods capable of identifying Temporary Coherent Scatterers (TS) have shown promise for pavement condition analysis. Regularly acquired meter- to 10 meter-scale resolution NISAR data would be useful to further develop this application. Due to its low SNR expectations on pavements at L-band frequencies, and moderate spatial resolution, NISAR would likely be limited in performance for this application.

Needs: Regular repeated SAR observations with high resolution (for further application development); Deformation maps;
End User Community: US Department of Transportation, state transportation agencies

Recommendations/Findings

The hazard and infrastructure monitoring breakout group agreed on the following findings and recommendations for the proposed NISAR mission:

1. InSAR can detect slow ground movements of non-tectonic geological hazards that can serve to map the geographic extent of the hazard and, in some cases, identify precursors. The most effective techniques for detecting such movements involve InSAR time series analysis.
    a. The NISAR strategy of regular frequent observations along a repeated path is effective for monitoring of these hazards.
    b. The finest resolution measurements should be made maximize performance
    c. The latency should be low (hours) to intermediate (days) to maximize utility
    d. Single polarization measurements are sufficient as long as they are consistent
2. Regular observations (several acquisitions per season) over most relevant infrastructure corridors (the corridors connecting major cities on East and West Coast) are required to meet the needs of the transportation infrastructure community
3. High-resolution (80MHz mode) data may be necessary to meet the needs for bridge and pavement monitoring. The group recommends major transportation corridors be combined with major urban centers to form zones reserved for 80MHz-mode acquisitions.
4. Regular 20MHz mode data may be sufficient for mapping geophysical hazards near transportation corridors
5. Deformation time series from processing of InSAR stacks are the preferred data type for the infrastructure community and will facilitate assessments of geological hazards, bridge stability, as well as embankment and levee safety.
6. A combination of SBAS-type, PS-type and TS-type processing results would be ideal to serve the full range of information needs.
7. Additional coherent and incoherent change detection data may be useful for identifying pavement breakup.
8. GIS-ready data formats (shapefiles; GeoTiff; …) are preferred in order to incorporate into existing GIS frameworks.

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6. Workshop Organization

This appendix contains more detailed information on the workshop

6.1 Workshop Agenda

28 October Tuesday			
8:30 am	*Paul Rosen*	Welcome from Project	
8:35 am	*David Applegate*	Welcome from USGS	
8:40 am	*Peg Luce*	Welcome from NASA Earth Sciences	
8:45 am	*Craig Dobson*	Welcome from NISAR Program	
8:50 am	*David Green*	Welcome from Applied Sciences	
8:55 am	*Paul Rosen*	Overview of Mission and Status, Baseline Science, Operational Plan, Data Products	
9:50 am	*Susan Owen*	Charge to Workshop	
10:00 am	*Break*		
10:15 am	Operational applications invited talks		
10:15	*Anup Das (ISRO), John Mathew (ISRO)*	Agriculture and other ISRO applications	
10:40	*Jerad Bales (USGS)*	Water Resources	
10:55	*Bruce Davis (Davis Consulting)*	Homeland Security, National Infrastructure	
11:10	*Evan Notman (USAID)*	Forestry & Wetlands	
11:25	*David Applegate (USGS)*	Disaster Response	
11:40	*Pablo Clemente-Colón (NOAA)*	Ocean-related Applications	
12:00 pm	*Lunch – USGS cafeteria*		
1:00 pm	*Susan Owen*	Charge to Breakout Session 1 – What are known and potential NISAR applications?	
1:15 pm	Breakout I – by Application Area (Topic/Room/Topic Co-Chairs)		
	Agriculture & Land Use	Room BA102C (Basement C)	*Paul Siqueira (UMass), Anup Das (ISRO)*
	Disaster Response & Recovery	Visitor Center Room	*Jon Nystrom, Kurt Schwoppe (ESRI), Tim Stough (JPL)*
	Forestry & Wetlands	Room 1B215	*Josef Kellndorfer (WHOI), Evan Notman (USAID), Uriel Kitron (Emory)*
	Hazard & Infrastructure Monitoring	Main Auditorium	*Shimon Wdowinski (UMiami), Andrea Donnellan (JPL)*
	Ocean Applications	Room BA102A	*Ben Holt (JPL), Frank Monaldo, Xiaofeng Li (NOAA)*

		(Basement A)	
	Water Resources & Hydrology	Room BA102B (Basement B)	*Brian Conway (AZDWP),Tom Farr (JPL)*
2:45 pm	*Break*		
3:00 pm	Reports from Breakout 1 & discussion		
4:00 pm	Welcome from Suzette Kimball, Acting Director of USGS		
4:05 pm	Panel discussion to identify inputs/operational constraints. Moderator: *Gerald Bawden (NASA)* Panelists: *Charlie Mandeville (USGS), Frank Monaldo (NOAA), Rick Mueller (USDA), Paul Rosen (NISAR project), Craig Dobson (NASA)*		
5:00 pm	*Adjourn*		
29 October Wednesday			
8:30 am	Lightning Talks on Innovative Techniques for SAR Applications		
	Kevin Schaefer (National Snow and Ice Data Center)	Permafrost Applications of InSAR	
	Daniele Perissin (Purdue)	Urban multi-temporal InSAR processing	
	Laura Bourgeau-Chavez (MTRI)	Improving Soil Moisture Retrieval with Polarimetric SAR data	
	Elijah Ramsey (USGS)	Mapping coastal marsh dieback and recovery with Optical VI and Radar HV	
	Peter Mouginis-Mark (UHawaii)	Sea level rise with NISAR	
9:00 am	*Susan Owen*	Charge to Breakout Session II – Applications requirements and current NISAR data products/observation plan	
9:15 am	Breakout II - by application area (same as Breakout I)		
10:45 am	*Break*		
11:00 am	Reports from Breakout II & discussion		
12:00 pm	*Lunch – USGS Cafeteria*		
1:00 pm	*Susan Owen*	Charge to Breakout session III: Discuss discipline product needs (divided by discipline)	
1:15 pm	Breakout III – by application area (same as Breakout I)		
2:45 pm	*Break*		
3:00 pm	Report from Breakout III & discussion		
4:15 pm	Summary and meeting conclusion		
5:00 pm	*Adjourn*		

6.2 List of attendees

First Name	Last Name	Company	Registrant Type
Mohamad	Abdalhalim	AL AMR Group	Remote Participation
Mohamed	Aly	University of Arkansas	Remote Participation
Falk	Amelung	University of Miami	Workshop
Eric	Anderson	University of Alabama in Huntsville / Earth System Science Center	Remote Participation
Kim	Angeli	USGS	Workshop
David	Applegate	U.S. Geological Survey	Workshop
Matt	Arkett	Canadian Ice Service	Workshop
Mike	Aslaksen	NOAA/National Geodetic Survey	Workshop
Noname	Aslan	Indiana University	Workshop
Don	Atwood	Michigan Tech Research Institute	Workshop
Kader	BA	Deparement of Geology	Remote Participation
Scott	Baker	UNAVCO, Inc	Workshop
Jerad	Bales	U.S. Geological Survey	Workshop
Zubair	Bangroo	Kashmir University	Remote Participation
William	Barnhart	USGS	Workshop
Gerald	Bawden	NASA	Workshop
Teresa	Baxter		Remote Participation
Noa	Bechor	MIT	Remote Participation
Rachel	Bird	Surrey Satellite Technology Ltd	Workshop
Diana	Borda Beltran	UQAM	Remote Participation
Laura	Bourgeau-Chavez	Michigan Technological University	Workshop
Steve	Bowman	Utah Geological Survey	Workshop
Jody	Boyd	Environment Canada	Remote Participation
Leah	Braithwaite	Canadian Ice Service	Workshop
John	Callahan	Delaware Geological Survey	Remote Participation
Manab	Chakraborty	Space Applications Centre (ISRO)	Remote Participation
Catherine	Champagne	Agriculture and Agri-Food Canada	Remote Participation
Bruce	Chapman	JPL	Workshop
Alok	Chatterjee	JPL	Workshop
Estelle	Chaussard	UC Berkeley	Workshop
Gerald	Checka	GrandVinsoft	Remote Participation
Albert	Chen	Stanford University	Workshop
Jennifer	Clapp	NOAA/NESDIS	Remote Participation
Pablo	Clemente-Colón	U.S. National Ice Center	Workshop
Brian	Conway	Arizona Department of Water Resources	Workshop
Cynthia	Dacre	MDA	Workshop
Anup Kumar	Das	Space Applications Centre, Indian Space Research Organization	Workshop
Andrew	Davidson	Agriculture Canada	Remote Participation
Bruce	Davis	Davis Consulting	Workshop

Roger	De Abreu	Canada Centre for Remote Sensing	Remote Participation
Elias	Deeb	US Army Cold Regions Research and Engineering Laboratory	Workshop
Manohar	Deshpande	NASA Goddard Space Flight Center	Workshop
Craig	Dobson	NASA	Workshop
Andrea	Donnellan	Jet Propulsion Laboratory/California Institute of Technology	Workshop
Xueyang	Duan	Jet Propulsion Laboratory	Workshop
Sanghamitra	Dutta	NASA	Workshop
John	Dwyer	USGS	Workshop
Jonathan	Epps	University of Houston	Workshop
Tom	Farr	JPL	Workshop
Heresh	Fattahi	University of Miami	Remote Participation
Kurt	Feigl	University of Wisconsin-Madison	Workshop
Yuri	Fialko	UCSD	Workshop
Eric	Fielding	Jet Propulsion Lab, Caltech	Workshop
Africa	Flores	University of Alabama in Huntsville/SERVIR	Remote Participation
Ralph	Foster	APL/University of Washington	Workshop
Marsha	Freeman	Executive Intelligence Review	Workshop
Gareth	Funning	University of California, Riverside	Workshop
Oscar	Garcia	FSU	Workshop
Maggi	Glasscoe	NASA Jet Propulsion Laboratory	Workshop
PRABHA	GOPINATHAN	Amrita Vishwa vidyapeetham	Remote Participation
David	Green	NASA	Workshop
Laurel	Gutenberg	George Mason University	Workshop
Bill	Hammond	University of Nevada, Reno	Workshop
Leif	Harcke	Jet Propulsion Laboratory	Workshop
scott	Hensley	Jet Propulsion Laboratory	Workshop
Everett	Hinkley	U.S. Forest Service	Remote Participation
Ben	Holt	JPL	Workshop
Edward	Hoppe	Virginia Center for Transportation Innovation and Research	Workshop
Vita	Hoyles	Ducks Unlimited Canada	Remote Participation
Brian	Huberty	U.S. Fish & Wildlife Service	Remote Participation
Kenneth	Hudnut	USGS	Workshop
Go	Iwahana	University of Alaska	Workshop
Christopher	Jackson	NOAA NESDIS STAR	Workshop
Ben	Jai	JPL	Workshop
ANMOL	JALALI	IISC	Remote Participation
Aleksandar	Jelenak	The HDF Group	Workshop
Liza	Jenkins	Michigan Tech Research Institute	Workshop
Shiguo	Jiang	State University of New York at Albany	Workshop

Mike	Johnson	Office of Science and Technology, NWS (NOAA)	Workshop
John	Jones	U.S. Geological Survey	Workshop
Sharon Monica	Jones	NASA	Remote Participation
Alfred	Kalyanapu	Tennessee Technological University	Workshop
Eric	Kasischke	NASA HQ	Workshop
Shannon	Kaye	Environment Canada	Remote Participation
Josef	Kellndorfer	Woods Hole Research Center	Workshop
Unmesh	Khati	Indian Institute of Technology Bombay	Remote Participation
Yunjin	Kim	JPL	Workshop
Uriel	Kitron	Emory University	Workshop
Drew	Kittel	NASA/GSFC	Workshop
Narendran	Kodandapani	Administrative Staff College of India	Remote Participation
Chandra	Kondragunta	NOAA	Workshop
Anatoliy	Koshulko	Geosphere S&T	Remote Participation
Susan	Kotikot	University of Alabama in Huntsville/SERVIR	Remote Participation
Hayati	Koyuncu	Jeodijital Ltd.Sti.	Remote Participation
Vineet	Kumar	IIT Bombay	Remote Participation
Deepak	Kumar	Central University of Karnataka	Remote Participation
Nettie	La Belle-Hamer	Alaska Satellite Facility	Workshop
David	Lagomasino	USRA GESTAR/NASA GSFC	Workshop
Megan	Lang	UMD Department of Geographical Sciences	Workshop
Hyongki	Lee	University of Houston	Workshop
SeungKuk	Lee	NASA/GSFC	Workshop
Xiaofeng	Li	NOAA/NESDIS	Workshop
Scott	Lindsey	NOAA/National Weather Service	Workshop
Kenneth	Linthicum	USDA - ARS	Workshop
Zhen	Liu	JPL	Workshop
Claire	Loe	CDC	Remote Participation
Erika	Lomeli-Uribe	NASA's AERO Institute	Workshop
Yunling	Lou	Jet Propulsion Laboratory	Workshop
Zhong	Lu	Southern Methodist Univ	Workshop
Paul	Lundgren	JPL	Workshop
John	Mathew	NRSC, ISRO	Workshop
Gari	Mayberry	USAID and USGS	Remote Participation
Bruce	McKenzie	Naval Oceanographic Office	Remote Participation
Charles	Meertens	UNAVCO	Workshop
Daniel	Melendez	NOAA	Remote Participation
David	Meyer	USGS/EROS	Workshop
Franz	Meyer	University of Alaska Fairbanks	Workshop
Mark	Middlebusher	Vencore, Inc.	Remote Participation
Bruce	Molnia	USGS	Workshop

Frank	Monaldo	Johns Hopkins APL	Workshop
Enrique	Montano	UMD	Workshop
Paul	Montesano	Sigma Space Corp/ NASA GSFC	Workshop
Andrew	Moore	NASA	Workshop
Peter	Mouginis-Mark	University of Hawaii	Workshop
Lee	MoungJin	Korea Environment Institute	Remote Participation
Rick	Mueller	usda/nass	Workshop
James	Munger	Northrop Grumman	Remote Participation
John	Murray	NASA	Workshop
Reginald	Muskett	Geophysical Institute, University of Alaska Fairbanks	Workshop
Marius	Necsoiu	Southwest Research Institute	Workshop
Andrew	Newman	Georgia Institute of Technology	Workshop
Jeremy	Nicoll	Alaska Satellite Facility	Workshop
Evan	Notman	USAID	Workshop
Jon	Nystrom	ESRI	Workshop
Batuhan	Osmanoglu	USRA / NASA GSFC	Workshop
Susan	Owen	Jet Propulsion Laboratory	Workshop
Jay	Parker	Jet Propulsion Laboratory	Workshop
Jay	Parrish	Jay Parrish, LLC	Workshop
Alicia	Peduzzi	US Forest Service	Workshop
Daniele	Perissin	Purdue	Workshop
Chris	Peter	MDA Information Systems LLC	Workshop
Birgit	Peterson	ASRC Federal InuTeq	Remote Participation
William	Pichel	NOAA/NESDIS/STAR	Workshop
Marilee	Pregitzer	Canadian Ice Service	Workshop
Matt	Pritchard	Cornell University	Workshop
Serenity	Purcell	Smithsonian Institution	Workshop
Bruce	Quirk	U.S. Geological Survey	Remote Participation
Paul	Raby	NGA	Workshop
Maryam	Rahnemoonfar	Texas A&M University-Corpus Christi	Remote Participation
Elijah	Ramsey III	US Geological Survey	Workshop
Jennifer	Rocca	NASA Jet Propulsion Laboratory	Workshop
Paul	Rosen	Jet Propulsion Laboratory	Workshop
Richard	Ross	U.S. Naval Research Laboratory	Workshop
Glen	Russell	FEMA	Workshop
Sassan	Saatchi	JPL/CALTECH	Remote Participation
Natalia	Sanchez	JPL	Workshop
Carolina	Santos	MSU	Workshop
Jeanne	Sauber	NASA GSFC	Workshop
Kevin	Schaefer	National Snow and Ice Data Center	Workshop
David	Schmidt	University of Washington	Workshop
Susan	Schoenung	NASA Ames Research Center / BAERI	Workshop
Kurt	Schwoppe	ESRI	Workshop
Ian	Sein	G3/7, ARNORTH	Workshop
Pamela	Serafino	NGA	Remote Participation

Joe	Sexton	Global Land Cover Facility, University of Maryland	Workshop
Manoochehr	Shirzaei	Arizona State University	Workshop
Marc	Simard	JPL	Workshop
Ramesh	SINGH	Chapman University	Remote Participation
Himanshi	Singhal	University of Colorado Boulder	Remote Participation
Paul	Siqueira	University of Massachusetts	Workshop
Gregory	Snyder	USGS	Workshop
Xiao-Peng	Song	University of Maryland	Remote Participation
Michael	Spence	NOAA, NIC	Workshop
Tim	Stough	NASA JPL	Workshop
Guoqing	Sun	University of Maryland	Workshop
GA Shanmugha	Sundaram	Amrita Vishwa Vidyapeetham University	Remote Participation
Swati	Tak	mdsu	Remote Participation
Medhavy	Thankappan	Geoscience Australia	Remote Participation
Kristy	Tiampo	Western University	Workshop
Amit	Tiwari	Banaras Hindu University	Remote Participation
Nathan	Torbick	Applied Geosolutions	Workshop
Michael	Turk	NOAA/NESDIS	Workshop
Daniel	Ueno	Office of Naval Research Global	Workshop
Ranga Raju	Vatsavai	North Carolina State University	Workshop
Augustus	Vogel	Office of Naval Research Global	Remote Participation
Chris	Wackerman	General Dynamics AIS	Workshop
Christelle	Wauthier	The Pennsylvania State University	Workshop
Shimon	Wdowinski	University of Miami	Workshop
Brian	Wee	National Ecological Observatory Network, Inc.	Workshop
Matt	Wei	University of Rhode Island	Remote Participation
Jessica	Wempen	University of Utah, Dept. of Mining Engineering	Workshop
Rick	Wessels	U.S. Geological Survey	Workshop
Tracy	Whelen	University of Massachusetts Microwave Remote Sensing Lab	Workshop
Jim	Whitcomb	NSF	Workshop
Charles	Wicks	USGS	Remote Participation
Sylvia	Wilson	USGS	Workshop
Robert	Winokur	Michigan Tech University	Workshop
Lucia	Woo	NASA GFSC / Sigma Space	Workshop
Paul	Woodford	KEYW Corporation	Workshop
Xiaohua	Xu	UCSD/SIO	Workshop
Banghua	Yan	NOAA/NESDIS/OSPO	Remote Participation
Soni	Yatheendradas	ESSIC/UMD	Workshop
Qin	Yu	GWU	Remote Participation
Sang-Ho	Yun	Jet Propulsion Laboratory	Workshop
Howard	Zebker	Stanford Univ	Workshop
Xiwu	Zhan	NOAA-NESDIS	Remote Participation

6.3 Organizing Committee

Susan Owen, *Chair and Deputy Program Applications Lead for NISAR*
Paul Rosen, *NISAR Project Scientist*
Gerald Bawden, Ben Holt, Josef Kellndorfer, Matt Pritchard, Howard Zebker, *Science Definition Team members*
Craig Dobson, *NISAR Program Scientist*
Francis Lindsay, David Green, Tim Stough, *Applied Science Disasters Program*
Eric Kasischke, *NASA Terrestrial Ecology Program*
Frank Monaldo, Xiaofeng Li, Bill Pichel, *NOAA*

6.4 Writing Committee

Susan Owen, Co-chair, *Deputy Applications Lead*, *JPL*
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Gerald Bawden, *NISAR Science Definition Team, NASA*
Pablo Clemente-Colón, *NOAA*
Brian Conway, *Arizona Dept of Water Resources*
Craig Dobson, *NISAR Program Scientist, NASA*
Andrea Donnellan, JPL
Tom Farr, *JPL*
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Ben Holt, *NISAR Science Definition Team, JPL*
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Tim Stough, *Associate Applied Science Disasters Program Manager, JPL*
Shimon Wdowinski, *University of Miami*
Sang-Ho Yun, JPL
Howard Zebker, *NISAR Science Definition Team, Stanford University*

7. Applications Traceability Matrices

The links below were used for the workshop breakout sessions, and will be replaced with links on the NISAR webpage (nisar.jpl.nasa.gov). Please look on the NISAR webpage if these links are out of date. Some breakout sessions took notes on the same elements captured in these applications traceability matrices – as a result, they may contain less information but will be populated over time.

Forestry & Wetlands: http://goo.gl/jQ48sx

Agriculture & Land Use: http:// goo.gl/AwBk8q

Water Resources Hydrology: http://goo.gl/Z1M08z

Oceans, Sea Ice & Coastal Zone: http://goo.gl/Mv4dTa

Disaster Response & Recovery: http://goo.gl/9jsxry

Hazard & Infrastructure Monitoring: http://goo.gl/DCK3rX
Hazard & Infrastructure Monitoring notes:: http://goo.gl/FZLnY8

8. Mission Characteristics

The spacecraft would accommodate two fully capable synthetic aperture radar instruments, each designed as array-fed reflectors to work as scan-on-receive wide swath mapping systems, hereafter referred to as "SweepSAR". The mapping scenario calls for frequent sampling over broad areas to create time series and allow for noise reduction through stacking methods. Thus, a high-rate instrument and data downlink system are required. The average capacity of the envisioned data downlink would be of order 24 Tbits per day, supporting the instruments, which can produce at L-band from 72 Mbps in its lowest bandwidth mode to over 1500 Mbps in the most demanding high-bandwidth, multipolarization mode.

Table 1. NISAR Mission Proposed Characteristics

Element	Description
Proposed Launch Date	Late 2020
Orbit	12-day exact repeat, sun-synchronous, dawn-dusk, polar, ~740 km altitude
Mission Duration	3 years nominal, with extended mission fuel reserve
Science Data Downlink Approach	· 30-45 minutes of data downlink per orbit at 3.5 Gbps data rate through polar ground stations · 1 Gbps direct downlink to India over Indian ground stations
Observation Approach	· L-band multi-mode global radar imaging · S-band multi-mode targeted radar imaging · Dual-frequency capable · ~240 km swath for all modes · Full pol, multiple bandwidths up to 80 MHz · Near-zero Doppler pointing, fixed boresight · Primarily left or right looking, with occasional flip to the opposite side for better polar coverage
Mapping Approach	Current approach defines a reference mission with fixed modes over broad target areas

NASA contributions would include the L-band SAR instrument, including the 12-m diameter deployable mesh reflector and 9-m deployable boom and the entire octagonal instrument structure shown in Figure 1. In addition, NASA would provide a high capacity solid-state recorder (order 9 Tbits), GPS, 3.5 Gbps Ka-band telecom system, and an engineering payload to coordinate command and data handling with the ISRO spacecraft control systems. ISRO would provide the spacecraft and launch vehicle, as well as the S-band SAR electronics to be mounted on the instrument structure. The coordination of technical interfaces among subsystems would be a major focus area in the partnership.

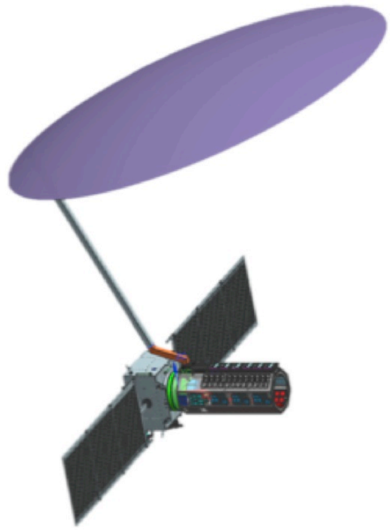

Figure 1. Artist's concept of NISAR spacecraft in flight configuration. Spacecraft velocity vector would be aligned with the long axis of the solar arrays. The L-band and S-band radar electronics are mounted on the octagonal structure pointing to the right.

NASA and ISRO would share science and engineering data captured at their respective downlink stations, and each organization would maintain their own ground processing and product distribution system. It is anticipated that the science teams and algorithm development teams at NASA and ISRO would work jointly to create a common set of product types and software. The project would deliver NISAR data to NASA and ISRO for archive and distribution. NASA and ISRO have agreed to a free and open data policy for these data. The spacecraft would launch on an ISRO GSLV-II launch vehicle into a polar sun-synchronous dawn dusk orbit.