New Research Directions for the National Geospatial-Intelligence Agency

ISBN
978-0-309-15865-7

70 pages
8 1/2 x 11
PAPERBACK (2010)

Steering Committee on New Research Directions for the National Geospatial-Intelligence Agency; Mapping Science Committee; National Research Council

NEW RESEARCH DIRECTIONS FOR THE NATIONAL GEOSPATIAL-INTELLIGENCE AGENCY
WORKSHOP REPORT

Steering Committee on New Research Directions for the
National Geospatial-Intelligence Agency

Mapping Science Committee

Board on Earth Sciences and Resources

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS • 500 Fifth Street, N.W. • Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by the National Geospatial-Intelligence Agency under Award No. HM1582-09-C0014. The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official Department of Defense position, policy, or decision unless so designated by other official documentation. Mention of trade names or commercial products does not constitute their endorsement by the U.S. government.

International Standard Book Number-13: 978-0-309-15865-7
International Standard Book Number-10: 0-309-15865-6

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet http://www.nap.edu.

Printed in the United States of America.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

STEERING COMMITTEE ON NEW RESEARCH DIRECTIONS FOR THE NATIONAL GEOSPATIAL-INTELLIGENCE AGENCY

KEITH C. CLARKE, *Chair,* University of California, Santa Barbara
LUC E. ANSELIN, Arizona State University, Tempe
ANNETTE J. KRYGIEL, Independent Consultant, Great Falls, Virginia
CAROLYN J. MERRY, Ohio State University, Columbus
SCOTT A. SANDGATHE, University of Washington, Seattle
MANI SRIVASTAVA, University of California, Los Angeles
JAMES J. THOMAS, Pacific Northwest National Laboratory, Richland, Washington

National Research Council Staff

ANNE M. LINN, Study Director
LEA A. SHANLEY, Postdoctoral Fellow
JASON R. ORTEGO, Research Associate
ERIC J. EDKIN, Senior Program Assistant

MAPPING SCIENCE COMMITTEE

KEITH C. CLARKE, *Chair,* University of California, Santa Barbara
LUC E. ANSELIN, Arizona State University, Tempe
CECILIA R. ARAGON, Lawrence Berkeley National Laboratory, Berkeley, California
BUDHENDRA L. BHADURI, Oak Ridge National Laboratory, Oak Ridge, Tennessee
SUSAN CARSON LAMBERT, Renewable Energy Strategies, LLC, Frankfort, Kentucky
LEWIS A. LAPINE, South Carolina Geodetic Survey, Columbia, South Carolina
CAROLYN J. MERRY, Ohio State University, Columbus
JAYANT SHARMA, Oracle Spatial, Nashua, New Hampshire
DANIEL Z. SUI, Ohio State University, Columbus
MICHAEL F. WORBOYS, University of Maine, Orono
MAY YUAN, University of Oklahoma, Norman

National Research Council Staff

ANNE M. LINN, Study Director
LEA A. SHANLEY, Postdoctoral Fellow
ERIC J. EDKIN, Senior Program Assistant

BOARD ON EARTH SCIENCES AND RESOURCES

ACKNOWLEDGMENTS

In response to a request from the National Geospatial-Intelligence Agency (NGA), the National Research Council (NRC) formed an ad hoc committee to organize a three day workshop to discuss new research directions for NGA. The workshop was held May 17–19, 2010, in Washington, D.C., and engaged a group of approximately 30 researchers in five core areas from different regions of the country. Gaps in knowledge regarding these five core areas were discussed, as were areas of research that could fill those gaps.

The NRC greatly acknowledges the work of the planning committee that designed this workshop. Keith C. Clarke of the University of California, Santa Barbara was the workshop moderator and served as chair of the workshop planning committee. Members of the planning committee were Luc E. Anselin, Arizona State University; Annette J. Krygiel, Independent Consultant; Carolyn J. Merry, Ohio State University; Scott A. Sandgathe, University of Washington; Mani Srivastava, University of California, Los Angeles; James J. Thomas, Pacific Northwest National Laboratory. All put a great deal of time, thought, and effort into planning an agenda, identifying and inviting speakers and attendees, and preparing a detailed agenda book that included a list of select references and white papers on these five core areas. Committee members also served as moderators and rapporteurs for individual breakout sessions.

For providing excellent workshop presentations intended to orient attendees regarding the subject matter to be discussed, NRC would like to thank Kathleen Carley, Carnegie Mellon University; Melba Crawford, Purdue University; Dave Ebert, Purdue University; Clive Fraser, University of Melbourne; Robert McMaster, University of Minnesota; Haesun Park, Georgia Tech University; Antonio Sanfillipo, Pacific Northwest National Laboratory; Dru Smith, National Oceanic and Atmospheric Administration, National Geodetic Survey; and May Yuan, University of Oklahoma. Additionally, the workshop would not have been successful without the important contributions of those who attended the event. A complete list of participants can be found in Appendix C. Discussions were informative, professional, and conducted in a cooperative spirit among, in large part, individuals who do not often have the opportunity to collaborate.

This workshop report was prepared by an ad hoc steering committee and NRC staff following the workshop. It represents the discussions of workshop participants as interpreted by an ad hoc steering committee.

This workshop report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published report as sound as possible and to ensure that the report meets institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

PEGGY AGOURIS, George Mason University
KATE BEARD-TISDALE, University of Maine, Orono
ANDREW CAMPBELL, Dartmouth College
HUAN LIU, Arizona State University
CHRIS RIZOS, University of New South Wales, Australia
AMITABH VARSHNEY, University of Maryland

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse nor did they see the final draft of the workshop report before its release. The review of this report was overseen by ROBERT B. HERRMANN, Private Consultant. Appointed by the National Research Council he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

OVERVIEW

PURPOSE OF THE WORKSHOP

The National Geospatial-Intelligence Agency (NGA) within the Department of Defense has the primary mission of providing timely, relevant, and accurate imagery, imagery intelligence, and geospatial information—collectively known as geospatial intelligence (GEOINT)—in support of national security. In support of its mission, NGA sponsors research that builds the scientific foundation for geospatial intelligence and that reinforces the academic base, thus training the next generation of NGA analysts while developing new approaches to analytical problems. Historically, NGA has supported research in five core areas: (1) photogrammetry and geomatics, (2) remote sensing and imagery science, (3) geodesy and geophysics, (4) cartographic science, and (5) geographic information systems (GIS) and geospatial analysis.

Positioning NGA for the future is the responsibility of the InnoVision Directorate, which analyzes intelligence trends, technological advances, and emerging customer and partner concepts to provide cutting-edge technology and process solutions. At the request of InnoVision, the National Research Council (NRC) held a 3-day workshop to explore the evolution of the five core research areas and to identify emerging disciplines that may improve the quality of geospatial intelligence over the next 15 years. This workshop report offers a potential research agenda that would expand NGA's capabilities and improve its effectiveness in providing geospatial intelligence.

WORKSHOP PLANNING

An NRC steering committee was established to organize the workshop, which was held in Washington, DC on May 17-19, 2010. The committee was asked to look ahead fifteen years without regard to NGA's immediate research needs, which are partially classified. In addition to the five core areas identified by NGA, the committee selected five cross-cutting themes that likely will become increasingly important to NGA: (1) beyond fusion; (2) forecasting; (3) human terrain; (4) participatory sensing; and (5) visual analytics. These themes were chosen based on their linkages with the core areas, on their utility in addressing the problems in geospatial science identified in a previous NRC study (NRC, 2006), and on the general needs of the intelligence community, as understood by the workshop steering committee. The research areas discussed at the workshop are defined in Box S-1.

BOX S-1
Description of Research Areas Discussed at the Workshop

Core Areas

Cartographic science—the discipline dealing with the conception, production, dissemination, and study of maps as both tangible and digital objects

Geodesy and geophysics

- Geodesy—the study of precisely measuring the size and shape of the Earth, its orientation in space, and its gravitational field in three-dimensional time-varying space
- Geophysics—the study of Earth physics, including the fields of meteorology, hydrology, oceanography, seismology, volcanology, magnetism, radioactivity, and geodesy

Geographic Information Systems (GIS) and geospatial analysis

- Geographic Information System—any system that captures, stores, analyzes, manages, and visualizes data that are linked to location
- Geospatial analysis—the process of applying analytical techniques to geographically-referenced data sets to extract or generate new geographical information or insight

Photogrammetry and geomatics

- Photogrammetry—the making of precise measurements from photographs, and the use of the measurements to reconstruct the two- and three-dimensional reference frame of the photograph and objects within it
- Geomatics—the discipline of gathering, storing, processing, and delivering geographic or spatially-referenced information

Remote sensing and imagery science

- Remote sensing—the science of acquiring information using instruments that are remote to the object, such as from aerial or spaceborne platforms
- Imagery science—the science of devising and using computational techniques for analyzing, enhancing, compressing, and reconstructing images

Cross-cutting Themes

Beyond fusion—aggregation, integration and conflation of geospatial data across time and space with the goal of removing the effects of data measurement systems and facilitating spatial analysis and synthesis across information sources

Forecasting—an operational research technique used to anticipate outcomes, trends, or expected future behavior of a system using statistics and modeling. It is used as a basis for management planning and decision making and is stated in less certain terms than a prediction

Human terrain—the creation of operational technologies that allow modeling, representation, simulation, and anticipation of behaviors and activities of both individuals and the social networks to which they belong, based on societal, cultural, religious, tribal, historical, and linguistic knowledge; local economy and infrastructure; and knowledge about evolving threats

Participatory sensing—tasks everyday mobile devices, such as cellular phones, to form interactive, scalable sensor networks that enable the public and professionals to gather, analyze, share, and visualize local knowledge and observations. Related terms include volunteered geographic information and community remote sensing.

Visual analytics—the science of analytic reasoning, facilitated by interactive visual interfaces. The techniques are used to synthesize information and derive insight from massive, dynamic, ambiguous, and often conflicting data.

Workshop participants included twenty-nine active researchers drawn from a wide range of disciplines, with special emphasis on the core areas and cross-cutting issues. In addition, five observers from NGA and other parts of the intelligence community participated in the discussions. Altogether, forty-eight participants attended the workshop, including NRC staff. On the first day of the workshop, participants focused on the NGA's five core areas, as well as new opportunities and challenges in these areas. On the second day, workshop participants discussed the five cross-cutting themes, focusing on the usefulness of these themes for geospatial intelligence. On the third day, participants reduced the results of the earlier discussions into a short list of promising research directions for the NGA. Participants also identified potential implications of implementing these research directions for the future workforce and other aspects of the scientific infrastructure. None of the material discussed or presented at the workshop was classified.

SUMMARY OF WORKSHOP DISCUSSIONS

This document summarizes the major points and ideas expressed during the workshop as documented by the steering committee. As such, the summary reflects the specific topics emphasized by the workshop presentations and discussions and may not be a comprehensive summary of all relevant topics and issues. Viewpoints in this summary do not necessarily represent the views of the workshop planning committee or the NRC, nor does the summary contain conclusions and recommendations.

Future Research Themes

Workshop participants examined NGA's five core areas and highlighted topics for new research in these fields. Subsequent discussions on the second and third days indicated that these core areas are in evolutionary flux and that emerging fields will need to be tracked and monitored. On the third day, workshop participants focused their discussion on ten future research directions that they thought would have relevance and value for the NGA. These research themes are:

- **Visual Analytics.** Areas within the field of visual analytics thought worthy of pursuit in the short to medium term included research on the computational modeling of large data sets and their organization for visual processing; models for integrating human intelligence and decision-making into GEOINT systems; building the scientific basis, e.g. theoretical frameworks, for visual analytics; and the integration into visual analytics of concepts from time-space analysis, multi-level data, uncertainty analysis, and human-computer interaction.

- **Integrating Sensors.** Workshop participants indicated that new sensors (e.g., hyperspectral and LiDAR (Light Detection and Ranging)), platforms (e.g., UAV drones, sensor networks and sensor webs, and "small satellites"), and modalities will require new paradigms and significant research in sensor modeling, sensor calibration, and sensor data fusion, as well as new methods to address the complexities of mission planning and adaptation of dynamic tasking. Workshop participants expressed the concern that the vast quantities of data collected will require the development of "smarter" real-time processing and georeferencing methods, perhaps coupled and on-board with sensor platforms. Concomitantly, significant research will be required in automated feature extraction.

- **Human Terrain/Behavior.** Workshop participants identified the following as key research areas within human terrain domain: geospatial data collection techniques for observing human behavior; geospatial integration of social, behavioral and cultural data; and the use of participatory data – policy for acquiring, influencing participation, dealing with security and privacy issues, mixing participatory data with traditional data, assessing reliability or credibility, and understanding cultural and social constraints on participatory data.

- **Participatory Sensing.** Workshop participants identified the following key elements of a research agenda that will enable effective use of Participatory Sensing in GEOINT: developing methods for planning and optimizing sensing and for incentivization of participants; addressing quality, uncertainty, and trustworthiness of participant-contributed data; and responsibly involving human participants, including addressing privacy and security concerns; integrating unplanned, unstructured participatory sensing data into GEOINT; and, incorporating prior information.

- **Improved Models of Space-Time**. The integration of time and space in GIS and geospatial analysis was seen by workshop participants as key to furthering the representation and understanding of complex dynamic physical and socio-behavioral processes. This will require the development of new and improved models that integrate the time structure of events, as well as their aggregates and narratives, with the spatial structure. Crucial in this is a theory of scale dependence in order to handle multiple resolution data bases and the integration of social, cultural and behavioral factors.

- **Development of New Paradigms for Conveying Certainty**. Almost all aspects of working group discussions touched on uncertainty as a long term issue that cut across all NGA core areas and that will require more robust treatment. Workshop participants felt that the following areas should be emphasized: the development of tools for establishing data and information quality at all stages of the information chain, from collection to decision making; the creation of methods to establish reliability of participatory sensing data; the development of methods to detect manipulation in participatory data; and means to convey reliability in visual data.

- **Improved geodetic/photogrammetric/remote sensing positioning.** Workshop participants noted that remote sensing, geodetic, and photogrammetry data will require improved positioning to be used effectively in geospatial intelligence. When satellite positioning data is not available, such as in buildings, underground or underwater, INS (inertial navigation system) will need to be developed to high accuracy levels. In addition, participants stated that improved gravity models are necessary to determine precise orbits and to reduce orbit errors associated with satellites.

- **Geospatial Information Retrieval and Extraction from Text.** Workshop participants stressed the importance of developing methods to use geospatial information to interpret unstructured and semi-structured textual information, as well as content analysis and semantic interpretation. More challenging is integrating information from a wide range of sources by anchoring them geospatially and understanding and characterizing the geographic variation of language.

- **Database Technology and Spatial Data Infrastructures (SDI).** Participants stated that research is needed to develop database technology and spatial data infrastructures that are capable of handling data that are multi-dimensional, spatially and temporally multi-scale, and multi-source, ranging from authoritative to participatory and public. Database requirements for extremely high spectral and spatial resolution, multimedia imagery, and free form text will continue to challenge most existing data schema and models.

- **Geospatial Narrative.** Many geospatial phenomena can be represented as narratives or stories—for example boats leaving and entering ports, or truck convoys moving from camp to airstrip—and difference from a known narrative becomes a mechanism by which the normal can be discriminated from the abnormal. A research track in geospatial narrative would focus on how to develop computational narratives within a spatio-temporal database, allowing narrative objects of any type to be automatically recognized and created, then manipulated for visualization and analysis.

IMPLICATIONS FOR THE SCIENTIFIC INFRASTRUCTURE

Participants devoted some of their attention to the implications of these research topics for scientific infrastructure. In particular, some felt that existing academic programs will need to respond strategically to these research challenges, which in turn will require new centers, resources, faculty and students. At the same time, some participants noted the need to protect existing research programs in core areas. The greatest challenge, however, will be dealing with the increasing need for interdisciplinary research and education.

– 1 –
INTRODUCTION

The mission of the National Geospatial-Intelligence Agency (NGA) is to provide timely, relevant, and accurate imagery, imagery intelligence, and geospatial information—collectively known as geospatial intelligence—in support of national security. To help carry out its mission, NGA sponsors research aimed at building the scientific foundation for geospatial intelligence and reinforcing the academic base, which provides new approaches to solving difficult analytical problems and also trains the next generation of NGA analysts.

Historically, NGA has supported research in five core areas:

- photogrammetry and geomatics
- remote sensing and imagery science
- geodesy and geophysics
- cartographic science
- geographic information systems (GIS) and geospatial analysis

Some of these areas have been used for defense and intelligence purposes for decades and even centuries (Box 1.1) and ongoing technological and scientific advances continue to make them useful today. For example, digital photogrammetry and digital imaging have completely replaced and substantially improved upon hardcopy photography and mechanical image rectification. Other recent advances that could improve geospatial intelligence draw on disciplines and approaches not traditionally supported by NGA. For example, efforts to wage a counterinsurgency in Afghanistan have highlighted the need for intelligence that integrates characteristics of the physical environment with information on the people, including the local economics, identity of landowners, and incentives for obtaining cooperation from powerbrokers and villagers (Flynn et al., 2010). This evolution of disciplines and new approaches for producing geospatial intelligence also affects the future workforce available to NGA.

Within this context, H. Gregory Smith, NGA Chief Scientist, asked the National Research Council to convene a workshop to explore the evolution of the five core areas and to identify emerging disciplines that may improve the quality of geospatial intelligence over the next fifteen years. This report summarizes the discussions at the workshop.

BOX 1.1 Milestones in NGA Core Areas for Defense and Intelligence Purposes

Year	Event
1813	Congress authorizes the Topographical Engineers to conduct surveys to facilitate the safe movement of troops for the War of 1812
1862	Observation balloons are used to take aerial observations during Civil War campaigns in Virginia
1917	Aerial photography becomes a major contributor to battlefield intelligence during World War I
1922	Sounding data are collected from a Navy ship for the first modern bathymetric chart
1941	Second World War aviation enables photogrammetry, photo interpretation, and geodesy to replace field surveys
1953	Project U.S. Magnet is created to measure magnetic variations around the Earth; the program continued until 1994
1956	U-2 aircraft carry out manned reconnaissance missions, becoming the primary source for intelligence gathering over the Soviet Union and other denied areas
1960	Successful return of imagery from CORONA, the first photoreconnaissance satellite system in the world
1960	Development of a World Geodetic System (WGS 60), which defined a best-fitting ellipsoid and an Earth-centered orientation system and formed the basis of current global positioning systems
1966	Launch of the Geodetic Earth Orbiting Satellite, the first satellite for geodetic studies
1973	Start of the Special Mission Tracking Program to obtain atmospheric observational data in support of scientific space operations
1974	First electronic dissemination of near-real time, near-original quality access to national imagery to assist in rapid targeting and assessment of strategic threats
1987	The Navigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System (GPS) becomes operational, providing accurate and continuous data on position, velocity, and time under all weather conditions
1995	The Predator unmanned aerial vehicle (UAV) becomes operational
1996	Creation of Earth Gravity Model 96, improving accuracy in GPS readings, determination of satellite orbits, and geodetic satellite measurements
2000	The Shuttle Radar Topography Mission (SRTM) begins to acquire elevation data over about 80 percent of the Earth's surface using interferometric synthetic aperture radar
2006	Different versions of the RQ-4 Global Hawk, a Remotely Piloted Aircraft (RPA) designed for reconnaissance become operational in service.

SOURCE: Wikimedia, NGA historical reference chronology, <https://www1.nga.mil/About/OurHistory/Pages/default.aspx>.

NATIONAL GEOSPATIAL-INTELLIGENCE AGENCY

NGA is one of sixteen federal agencies responsible for national intelligence. Its focus is the exploitation and analysis of imagery and geospatial information to describe, assess, and visually depict physical features and geographically referenced activities on the Earth. Issues that have a component of "where" or "when" potentially fall under the purview of NGA.

Most of NGA's efforts are devoted to the provision of data, intelligence and services to users now and in the near future. Positioning the NGA for future capabilities is the responsibility of the InnoVision Directorate, which analyzes intelligence trends, technological advances, and emerging approaches to forecast possible environments and identify future needs. Demands for new kinds of information and the development of new capabilities for data collection have led to explosive growth in the quantity, diversity, and complexity of information, and placed new and more exacting requirements on information analysts. Future global developments—such as climate change, water scarcity, the spread of infectious disease, global financial/economic activities, warfare, terrorism, and nuclear proliferation—will further increase the complexity of geospatial intelligence by requiring the collection and analysis of new data on environmental and human factors and how they interconnect.

Future challenges facing NGA are both computational and scientific. A 2006 National Research Council (NRC) report focused on the former, identifying twelve "hard problems" in data collection, processing, and integration; speed of analysis; use of imagery; and data sharing that must be surmounted to improve geospatial intelligence (NRC, 2006). This workshop report discusses the science disciplines that form the foundation for solving these and other geospatial intelligence problems.

OVERVIEW OF THE WORKSHOP

Planning Committee

A National Research Council steering committee was established to organize the workshop and write a report. Committee members were selected for their expertise in the earth, geospatial, and computational sciences that are or are likely to become important to NGA, or for their experience with the intelligence community. The committee met in February 2010 to plan the workshop and again immediately following the workshop to begin writing the report.

The committee was asked to look ahead fifteen years without regard to NGA's immediate research needs, which are partially classified. In addition to the five core areas identified by NGA, the committee selected five cross-cutting themes that are likely to become increasingly important for GEOINT: beyond fusion, forecasting, human terrain, participatory sensing, and visual analytics. These were chosen based on their linkages with the core areas, on their utility in addressing the hard problems in geospatial science identified in a previous NRC study (NRC, 2006), and on the general needs of the intelligence community, as understood by the workshop steering committee. The research areas discussed at the workshop are defined in Box S-1.

Structure of the Workshop

The workshop was held in Washington, D.C., on May 17-19, 2010. The first day of the workshop focused on the NGA's five core areas. White papers written for the workshop traced the evolution of the core areas over the past few decades. Workshop presentations and working group discussions looked forward, focusing on new opportunities and challenges in these areas for NGA. On the second day, workshop participants discussed the five cross-cutting themes. Background journal articles and presentations provided an overview of the state of the science, and the working group discussions focused on the usefulness of the cross-cutting themes for geospatial intelligence. On the third day of the workshop, participants focused the results of the earlier discussions into a short list of promising research directions for the NGA. Some participants also identified potential implications of implementing these research directions for the future workforce and other aspects of the scientific infrastructure. None of the material discussed or presented at the workshop was classified.

Workshop participants included twenty-nine active researchers drawn from a wide range of disciplines, with special emphasis on the core areas and cross-cutting issues. In addition, five observers from NGA and other parts of the intelligence community participated in the discussions. Altogether, forty-eight participants attended the workshop, including NRC staff.

ORGANIZATION OF THE REPORT

This report is the committee's summary of what transpired at the workshop. It reflects only those topics emphasized during workshop presentations, discussions, and background papers, and is not intended as a comprehensive summary of all topics and issues relevant to the research underlying the production of geospatial intelligence. Moreover, this report does not contain any consensus recommendations or conclusions. The documented observations or views contained in this report are those of individual participants or groups of participants and do not necessarily represent the consensus of the workshop participants or the committee.

Chapter 2 summarizes the presentations and working group results on NGA's core areas and the cross-cutting themes, respectively. Chapter 3 presents the short list of new research directions selected by workshop participants and discusses some implications of implementing them on the research infrastructure. Biographical sketches of committee members are given in Appendix A. The list of presenters, list of participants and meeting agenda are given in Appendices B, C, and D, respectively. Additional notes from the workshop brainstorming sessions are provided in Appendix E.

– 2 –
NGA CORE AREAS AND CROSS-CUTTING THEMES

NGA CORE AREAS

Photogrammetry and Remote Sensing

The topics of photogrammetry and remote sensing were tackled during the morning session of the first day of the workshop, May 17, 2010. Photogrammetry and remote sensing have experienced tremendous innovation over the last decade with the development of new sensing technologies, improvements in spectral and temporal resolution, and advances in automated feature extraction techniques. The workshop planning committee invited Dr. Clive Fraser of the University of Melbourne, Australia, and Dr. Melba M. Crawford of Purdue University, to provide an overview of photogrammetry and remote sensing, respectively, and to offer their thoughts on future research directions. This section summarizes Dr. Fraser's presentation, entitled "Spatial Information Extraction from Imagery: Recent Trends in Geomatics," Dr. Crawford's presentation, entitled "Advanced Sensing and Information Extraction: Synergies for Optical Sensing," and the discussion that followed.

Photogrammetry, a subset of remote sensing, obtains accurate two- and three-dimensional coordinates and information for physical objects and the environment through the processes of acquiring, measuring and interpreting photographic images. Geomatics is the discipline of gathering, storing, processing and delivering geographic or spatially-referenced information, and is largely concerned with calibration, measurement and three-dimensional representation of objects. Traditionally, photogrammetric technologies and techniques were limited to photographic images. According to Dr. Frasier, globally, the field is expanding to include the interpretation and mensuration of imagery obtained from a wide variety of sensors and platforms, including multispectral and hyperspectral images, Light Detection and Ranging (LiDAR), and radar data. For example, photogrammetry now routinely encompasses digital aerial imaging systems, with a recent emphasis on the development of medium format, single and multi-sensor cameras; high-resolution satellite imagery with better than 0.5-meter resolution; airborne LiDAR with increasing pulse and scan frequency and full waveform recording; and airborne and spaceborne radar, including imagery and InSAR for digital elevation model (DEM) extraction.

In addition, there is rapid development of mobile mapping systems equipped with synchronized navigation and imaging sensors, such as digital cameras installed in stereoscopic pairs, LiDAR, or both. Low-cost photogrammetric systems using calibrated consumer-grade digital SLR (single lens reflex) cameras and inexpensive software are becoming more available and accessible, even to the non-photogrammetrist. In some respects, Google Earth, NearMap, and PhotoSynth also might be considered photogrammetry as these software systems provide two- and three-dimensional representations that are derived from imagery. However, according to Dr. Frasier, these software systems lack the metric integrity inherent in photogrammetry, including issues of calibration, sensor modeling, georeferencing and rigorous data fusion.

Dr. Frasier identified several key research challenges for photogrammetry and geomatics, including sensor modeling and georeferencing, feature extraction, and above all, increased automation of the spatial information generation process. Several photogrammetric operations are routinely automated, including: interior and exterior orientation; control point recognition; elevation extraction with user input for refinement, checking, and correction; aerial triangulation with user input for ground control; orthophoto generation; some aspects of display and visualization; and three-dimensional scene generation in mobile mapping (Xiong and Zhang, 2010). However, the automated extraction of information (i.e., vector data) from photo-textured three-dimensional point clouds (such as those generated by terrestrial LiDAR scans) is still an area of ongoing research (e.g. Chen et al., 2007). Other areas of emerging research include: calibration of complex multi-sensor cameras and the alignment of cameras to inertial measurement units (IMUs) and LiDAR; sensor orientation modeling using rigorous sensor modeling versus rational polynomial functions (RPCs) for multi-scene processing of high-resolution satellite imagery; automatic feature extraction, particularly for building extraction, topographic mapping and utility mapping; monoplotting in the absence of stereo for close range —three-dimensional object reconstruction via single images and a digital elevation model (DEM); forensic measurement with consumer-grade cameras (van den Hout and Alberink, 2010); image sequence processing and analysis; enhanced object modeling and classification via full waveform LiDAR; biomass estimation via radar and LiDAR technologies (Kellndorfer et al., 2010); and enhanced classification for feature extraction. Dr. Frasier also noted the need for research in data fusion, which is discussed in Chapter 3.

To summarize Dr. Frazier's presentation, the principal challenge of photogrammetry and geomatics is centered on the automated generation of spatial information from multiple sources of imagery and ranging data generated by ubiquitous, integrated multi-sensor systems. While discussion on automating "feature extraction" highlights the challenges of automation, it is only a starting point and the solution is likely to involve a combination of research from traditional remote sensing as well as from the new "cross-cutting" disciplines. Higher spatial and temporal resolutions will be required to support a range of functions, such as change detection, monitoring, and GIS database update. Research needed to support these functions range from metric processing of remotely-sensed multi-sensor data to feature extraction and modeling.

In the second presentation, Dr. Melba M. Crawford of Purdue University focused on the state-of-the-art of optical remote sensing technologies. Remote sensing is the science of acquiring imagery and information about an object or phenomena using sensors that are wireless or not physically connected to the object, such as from airborne or spaceborne platforms. Remote sensing technologies include high resolution panchromatic and multispectral sensors; hyperspectral sensors, which collect tens to hundreds of narrow spectral bands continuously across the electromagnetic spectrum; and LiDAR, which includes full waveform systems and photon counting techniques. Common challenges in remote sensing include information extraction, data storage and data product dissemination. Because hyperspectral imagery is collected over narrow bandwidths across a wide range of the electromagnetic spectrum, it is possible to extract detailed spectral patterns for a variety of rock and mineral types and for simple land cover/vegetation classification. These spectral patterns, in turn, can be used for image classification and chemical content analysis. Thus, hyperspectral imagery potentially can provide improved capabilities for atmospheric correction, characterization of targets of interest, pixel unmixing, anomaly detection, classification, and increased sensitivity to spatial and temporal variations. Improved atmospheric corrections are particularly important for multi-temporal or multi-sensor analysis, while improved sensitivity to spatial and temporal variations is important in parts of the world where ground-truthing is limited or impossible. The challenges of hyperspectral sensing, however, are the enormity and redundancy of the data sets, the significant number of parameters needed to extract information, and the sensitivity to spatial and temporal variations in signatures.

Dr. Crawford emphasized that machine learning focuses on the design and development of algorithms that allow computers to progressively learn behaviors based on empirical data, such as from sensor data or databases. Three machine learning techniques that show promise for extracting information from hyperspectral imagery are: 1) nonlinear manifold learning; 2) semi-supervised learning; and 3) active learning. Nonlinear manifold approaches, which reduce the dimensionality of the imagery via non-linear transformations, include local linear embedding (LLE) (Roweis and Saul, 2000), isometric feature mapping (ISOMAP) (Tenenbaum et al, 2000), and the commonly used Kernel Principal Components Analysis (PCA) (Scholkopf, 1998). Semi-supervised learning makes use of both labeled and unlabeled data for training to generate a classification, and typically assumes that the labeled and unlabeled samples are from the same population. The unlabeled samples are used primarily to recover under-represented characteristics of labeled samples. Semi-supervised approaches include: self-learning with ML classifier (Jackson and Landgriebe, 2001); Transductive Support Vector Machines (SVM) (Bruzzone et al, 2006); and semi-supervised SVM (Mingmin et al, 2007). Lastly, active learning mines the unlabeled data for information and interacts with the classifier in order to construct the training pool for supervised and semi-supervised learning.

In summary, Dr. Crawford outlined future research opportunities for advanced optical remote sensing, including interdisciplinary research in data exploitation; sophisticated visualization techniques and integration with data analysis; new computational paradigms for analysis and modeling; sensor integration and sensor web applications; and integration of advanced optical sensor data with three-dimensional and four-dimensional GIS functionality. Critical challenges include the focus on traditional data sources and methods of analysis, the gap between research and operational missions, and the need to train GEOINT professionals.

Working Group Reports

Working group reports on photogrammetry, geomatics, and remote sensing indicated that these fields are moving in the direction of four-dimensional mapping, including time, with the goal of achieving the ability to search for and analyze events and scenarios. This is a departure from the traditional use of sequential rectified images to detect and locate changes on the landscape. Workshop participants remarked on the critical need for hyperspectral and LiDAR data and on the growing importance of data acquired from non-traditional platforms, such as networks of spatially distributed sensors (i.e., sensor networks and sensor webs), unmanned aerial vehicles (UAV), drones, "small satellites," consumer-grade cameras, and cell phones. For example, cameras, sound recording devices, and inertial mapping systems carried by individuals are being used for real-time mapping of interior spaces. The amount of data produced by these systems, however, can be significant and thus expensive and time-consuming to transmit from the point of acquisition to the point of processing. Therefore, constant data streams will need to be processed and georeferenced closer to the data acquisition system to ensure useful information in near real-time. More comprehensive metadata also will become available.

Workshop participants also noted that remotely sensed data needs to be integrated with other data sets, such as geographic information systems (GIS) data layers, data from metric/non-metric technologies, socio-economic data, cultural information, contextual data, and time series. Text information, for example, can be linked with remote sensing data to aid classification and to improve event and scenario recognition. Change analysis can be enhanced beyond the process of measurement and classification to model dynamics, behavior, and prediction. Atmospheric impacts also need to be exploited as signals.

Blending of information and integration of open source data provide new methods for information fusion. However, incorporation of these various kinds of data results in data of mixed type and unknown quality. Participants focused on data quality issues that will need to be addressed, including: reliability, quality assurance and control, system calibration, with a more comprehensive use of supporting environmental information. Uncertainty and error need to be integrated into multi-sensor fusion models and methods of information extraction and analysis. Characterization of multiple sources of uncertainty, sensor errors, data confidence, and models (empirically vs. theoretically-based) needs to be performed. Advanced statistical estimation, automation, modeling and data processing, numerical methods and optimization techniques also can be incorporated. State-of-the-art algorithms can be better utilized.

Workshop participants suggested that these complex problems will require new strategies that are interdisciplinary in nature and that incorporate multi-scale, multi-temporal, and multi-resolution data integration and analysis. Situationally-aware analysis tools will need to be tailored for specific end purposes. The infrastructure required to handle the massive volumes of data will be equally important, such as data storage, compression, distribution, and throughput to the analyst. More tools, better knowledge-based methods, visual analytics, metadata generation, process automation, and data mining for a specific sensor can augment the information flow to the image analyst. The analyst will require more than just imagery and knowledge of the physical landscape, including data on the dynamics and social environment.

The five traditional NGA core areas are being augmented with the blending of the fields of computer science, statistics, electrical and computer engineering, geodesy, geography and bioinformatics.

Cartography, Geodesy, GIS and Geospatial Analysis

The workshop planning committee invited Dr. Robert McMaster, Department of Geography, University of Minnesota, Dr. Dru Smith, Chief Geodesist, National Oceanic and Atmospheric Administration (NOAA), National Geodetic Survey (NGS), and Dr. May Yuan, University of Oklahoma, to provide an overview of cartography, geodesy, and geospatial analysis, respectively, and to offer their thoughts on future research directions. This section summarizes their presentations and the discussion that followed.

The first keynote address, given by Dr. McMaster, focused on “Trends in cartographic science.” Dr. McMaster revisited research priorities outlined by the University Consortium on Geographic Information Science (UCGIS) in the late 1990s. The long term challenges were listed as: spatial ontologies, geographic representation, spatial data acquisition and integration, the use of remotely acquired data in GIScience, scale, spatial cognition, analysis and modeling of space/time data, dealing with uncertainty, and visualization. Other challenges included seeking GIS’s role within society, and geographic information engineering (i.e., distributed computing, the future spatial information infrastructure, data mining and knowledge discovery). Pressing short term challenges were listed, and among these geocomputation and geographic information security were highlighted.

Dr. McMaster then focused his attention on three important themes in current cartographic research: scale and generalization (i.e., the process of simplifying information on a map, e.g., the boundary, especially as the scale of the map becomes smaller); geographic visualization; and public participation mapping (Elwood 2006, Sieber 2006, Tulloch 2008) and volunteered geographic information (Goodchild 2007, Elwood 2008, Flanagin and Metzger 2008). Research questions of interest included understanding how scale affects human perception, how scale can be measured and characterized, how to automate scale change in mapping systems, and how scale and scale change affect information content, analysis and conclusions about spatial patterns and processes. Under visualization, collaborative systems, information visualization, spatialization, multivariate mapping and animation were seen as in need of basic research. Lastly, the social implications of GIS was discussed, including showing a recent rise in participatory mapping and volunteered geographic information collected via on-line mapping systems.

The second keynote, presented by Dr. Smith, titled “An optimist’s 20 year look ahead at geodesy and geophysics,” compared the predictions formulated by leading past reports on geodesy with the current state of the art (i.e., Whitten 1963, NRC 1985, Sanso 2003, IVS 2006, Plag and Pearlman 2009, Wanninger 2008).

Significant innovations in geodesy raised in these historical glimpses of the future include satellite geodesy, an earth centered reference frame, distancing by laser, and the measurement of gravity potentials. A 1985 NRC report (NRC, 1985) raised the advent of the Global Positioning System, solutions to changes in geodesic measurements, merging absolute and relative geodesy, and improving inertial systems. In 2001, GPS expert Richard Langley forecast that by 2084, GPS would be capable of 1mm accuracy in seconds, for $10 by a wristwatch (Wanninger, 2008). A 2003 International Association of Geodesy report forecast that a global reference frame would be available accurate to millimeters horizontally and centimeters vertically, that the earth’s geodetic sub-systems would be modeled as interacting, and that geodesy would involve combining massive data sets. Lastly, a 2009 study (Plag and Pearlman, 2009) noted that geodesy would need to meet the needs of global change with continuous operational monitoring systems, while integrating new imagery, such as gravimetry, with point-based data in GIS. Many of these forecasts have now been realized, but some remain elusive.

Dr. Smith’s own forecasts of the geodetic systems of the future included pervasive Global Navigation Satellite Systems (GNSS) with sub-meter instantaneous precision, widespread use of EGM08 and a world height system in military theaters, improved gravimetric imaging, and drastically more accurate atomic clocks. These would support such applications as sea-level rise monitoring, navigation in the Arctic, earthquake and tsunami warning systems, and non-GNSS systems for navigation and positioning indoors and underground.

Based on this assessment, Dr. Smith identified five main themes for research in geodesy and geophysics:

- how to get optimal fusion of super-massive quantities of data;
- how to fold cutting edge new technologies into operational use;
- how to get exterior positions to centimeter (and in the future millimeter) accuracy in real time;
- how to set up a long term Earth monitoring service, with geodesy as the foundation; and,
- how to deal with a public that is increasingly "position capable," but ignorant of geodesy.

The third keynote address, delivered by Dr. Yuan, explored "Spatial integration and spatiotemporal inspiration." Dr. Yuan characterized the state of the art in GIS as reflecting spatial integration, both horizontally through conflation and vertically through overlay. The challenges to spatial integration were seen as developing a spatially integrated framework of data, models and decision-support systems, doing vertical as opposed to horizontal integration, and analysis and modeling (Hornsby and Yuan, 2008). Current solutions include mash-ups and participatory systems, and geosensor webs such as WeatherSense. The future was viewed as "spatiotemporal inspiration." Specific challenges included dealing with space-time memory and space-time clues, space-time ordering and spatiotemporal language, cyber GIS and real-time applications, and space-time and geographic dynamics (Pultar et al., 2010). Dr. Yuan contrasted the geographic measurement framework, the GIScience relational object model of geographic space, and her own model of geographic dynamics, which includes activities, events and processes. Examples from atmospheric systems were used as illustrations. Particular emphasis was given to the concept of a "narrative GIS," or the role of GIS as a compiler for spatial event sequences seen as "stories." Future research needs in spatiotemporal inspirations would require the GIS to support moving from forms to processes to narratives consisting of linked event sequences. Narratives can be transformed to possibilities (e.g. scenarios), which can be characterized by metrics to assess and create similarity gradients (e.g. by how much does this situation differ from the average, or from last year), which in turn can guide prediction and forecasts based on the probabilities.

Working Group Reports

In addition to reiterating a number of themes raised in the keynote presentations, the breakout groups formulated several topics in need of further research. With respect to cartographic science, the need to improve the speed of map presentation was noted, moving beyond tile-based mapping and an emphasis on the Mercator projection to continuous-scale mapping. Scale itself needs to be transcended from a purely cartographic focus to include semantics and temporal dimension, a theme echoed in the discussion of GIS and Geospatial Analysis. Similarly, the incorporation of volunteered geographic information was raised as important for both cartographic research and GIS. In terms of future technology, the extension of interactive cartography was suggested, by considering the cognitive effectiveness of geo-spatial technology to include eye tracking, brain sensing and the use of other body sensors.

Workshop participants' discussion of geodesy focused on the importance of global navigation satellite systems (GNSS) especially the Global Positioning System (GPS), the move towards ubiquitous geopositioning (e.g., multiple receivers, phone, navigation), and the need to integrate GPS in all aspects of geospatial technology. Ensuring user proficiency in the proper use and interpretation of positioning data is equally important. In addition, gravimetry, especially to improve our understanding of time dependent gravity, is an exciting new area of research. A third issue raised was the need to expand the ground-based continuously operated reference system (CORS, operated by the National Geodetic Survey), which provides GNSS data consisting of carrier phase and code range measurements in support of three dimensional positioning, meteorology, space weather, and geophysical applications throughout the United States, its territories, and a few foreign countries. Impressive progress has been obtained in geodetic accuracy, but improvements are needed in areas where GNSS does not work, such as under tree canopies, in urban and natural canyons, and underground/underwater. With respect to precision, participants expressed the desire to establish a geodetic reference frame at a sub-millimeter accuracy level and the next generation of positioning instrumentation and inertial navigation systems stable to the centimeter level over time. The importance of high performance computing to support such an effort was noted, for example as it relates to issues of reliability and latency associated with the handling of massive quantities of data.

Regarding GIS and Geospatial Analysis, several breakout groups stressed the importance of the temporal dimension. A true comprehensive space-time GIS and geospatial analytical framework remains to be developed. A second important theme was the incorporation of heterogeneous sources of information into a GIS. This includes information from unstructured sources (e.g., text), social and knowledge domains with GEOINT, and volunteered geographic information. A core concern and research need in this respect is the assessment and representation of the quality of that information (from authoritative and non-authoritative sources), specifically, benchmarking, the visual representation of quality, reliability and confidence and their interpretation by the user. The concept of social mapping was noted and the need for integration of geospatial and social networks.

A third theme centered on the concept of the GIS narrative and its expansion to multiple levels of explanation, involving the need to conceptualize complex information into a story line. A further understanding of how to work with the narrative framework is needed as well. Related to this is the overall communication of geospatial issues (both static and dynamic) and their visualization. Fourth, in terms of geospatial analytical methodology, the potential for game-based analytics was noted, as well as the need for automated service and workflow discovery to enable automatic tool application. The last two themes that emerged in several discussion groups were the need to develop proper (interdisciplinary) training and education to generate the needed workforce and an assessment of the current organization of NGA along the five traditional disciplines. Some concern was voiced that the latter may hamper interdisciplinary and collaborative investigation, which are viewed as key to obtaining significant research advances.

Specific topics outlined by the working groups are summarized in Appendix E.

CROSS-CUTTING THEMES

Forecasting, Participatory Sensing, and Visual Analytics

The topics of forecasting, participatory sensing, and visual analytics made up the morning session of the second day, May 18, 2010. Three keynote presentations set the stage for further discussion. Dr. Antonio Sanfillipo, Pacific Northwest National Laboratory, gave the initial keynote titled "Technosocial Predictive Analytics: Bridging the Gap between Human Judgment and Machine Reasoning." Forecasting is an operational research technique used to anticipate changes, outcomes, trends, or expected future behavior of a system using statistics and modeling. For example, geospatial forecasting can be used to anticipate the impact of climate change, and energy consumption on the power grid and critical infrastructure. In his presentation, Dr. Sanfillipo identified three research challenges: (1) to combine diverse elements of knowledge to promote model fidelity and reliability; (2) to link across diverse modeling algorithms to use the right tool for the right job and to leverage legacy models; and (3) to stimulate creative reasoning through collaborative work with interoperable models.

Dr. Cyrus Shahabi, University of Southern California, gave the second presentation, titled "Participatory Urban Data Collection: Planning and Optimization." Participatory sensing tasks everyday mobile devices, such as cellular phones, to form interactive, scalable sensor networks that enable the public and professionals to gather, analyze, share, and visualize local knowledge and observations. Dr. Shahali's key issue was the optimal placement of the sensors that people would use to collect geospatial data and major challenge was planning and optimization to enable the collection of useful data from a broad group of untrained participants. In addition, the speaker raised concerns regarding privacy and trust between volunteers and project organizers, which will need to be addressed. Several successful project examples were described, including participatory texture documentation (Banaei-Kashani,et al, 2010).

Dr. David S. Ebert, Purdue University, offered the third keynote on "Proactive and Predictive Visual Analytics." Since the publication of *Illuminating the Path the R&D agenda for Visual Analytics* (Thomas and Cook, 2005), the field of visual analytics has grown substantially. Visual analytics is the science of analytical reasoning facilitated by interactive visual interfaces. It is a multidisciplinary science, drawing upon the domains of knowledge discovery, cognitive and perceptual sciences, interaction science, decision sciences, geospatial analytics, scientific computing, graphics and visualization, statistical and information analytics, and data management. Dr. Ebert stated that visual analytics needs to provide an interactive, integrated discovery environment that can be user- and perceptually guided, balancing human cognition and automated computerized analysis to amplify human cognition. The key challenges for proactive and predictive spatiotemporal visual analytics mentioned by Dr. Ebert were: (1) making computational simulations and statistical analysis interactive; (2) integrating and analyzing massive and streaming multi-scale data for cross-scale visual analysis and to simulate multi-scale, multi-system, multi-source interactions; (3) creating seamless natural interaction with and multivariate, multidimensional representations of spatiotemporal environments, and also to develop new temporal and spatiotemporal directable and adaptive predictive models; (4) developing intuitive visual analytics for uncertainty and time; (5) integrating computer-human visual cognition environments to create interactive planning and decision-making environments; (6) adapting spatiotemporal analytics to integrate and perform with user-specified knowledge, context, constraints and boundaries; (7) adjusting algorithms to enable mobile context-sensitive analytics and balance local-remote distribution of work; and (8) adapting visual analytics to the user, environment, and sources of data. A recent suite of nine articles published in the *International Journal for Information Visualization* in Fall 2009 describe the first five years of progress in this science, including early success stories.

Working Group Reports

The working group participants noted that challenges in forecasting include predicting human behavior, the lack of theory, and the prior lack of integration with geospatial data and that spatial analytic methods, validation techniques and space-time issues need to be incorporated into predictive models. Participatory sensing was thought to be understudied in geospatial data. Challenges identified by participants include preserving individual privacy, dealing with unstructured and varying quality data, exploiting social networking tools, capturing the context of data, and encouraging participation. Visual analytics development was thought to require developing a repeatable body of knowledge within the geospatial field, that includes interactivity and visualization. New ideas could be derived by looking at aggregates and across scales. Additional challenges mentioned were dealing with space-time and massive data sets; developing metaphors, games, and animations for understanding pattern; improving modeling and simulation; and using high-performance computing and the proper depiction of data quality and error uncertainties.

Specific topics outlined by the working groups are summarized in Appendix E.

Beyond Fusion and Human Terrain

The workshop planning committee invited Dr. Haesun Park, Computational Science and Engineering School, Georgia Institute of Technology, and Dr. Kathleen Carley, Carnegie Mellon University, to provide an overview of data fusion and human terrain analysis, respectively. This section summarizes Dr. Park's presentation, entitled "Data and Visual Analytics for Information Fusion," Dr. Carley's presentation, entitled "Human Terrain—Assessing, Visualizing, Reasoning, Forecasting," and the discussion that followed. Data fusion is the aggregation, integration and conflation of geospatial data across time and space with the goal of removing the effects of data measurement systems and facilitating spatial analysis and synthesis across information sources. Human terrain is the creation of operational technologies that allow modeling, representation, simulation, and anticipation of behaviors and activities of both individuals and the social networks to which they belong, based on societal, cultural, religious, tribal, historical, and linguistic knowledge; local economy and infrastructure; and knowledge about evolving critical events.

In her keynote, Dr. Park made a distinction among early, middle and late data fusion options. These are sometimes termed object, situation, and threat fusion respectively in an intelligence context (Liggins et al., 2009). Early fusion is computer intensive, lacks engagement of the domain knowledge and requires a common feature representation. Late fusion reduces features to concept scores or weights, using voting and rank aggregation, and makes interrelations hard to interpret. Kernel functions were discussed as a means to achieve early fusion (Munoz and Gonzales, 2008). Examples of fusion of breast cancer data, images and audio data, photographs and fingerprints, and handwritten text were used. Methods of use in discriminating among instances, and identifying new instances were discussed. It was noted that for effective fusion, breakthroughs in mathematics, statistics, algorithms, software and systems would be necessary. According to Dr. Park, the key future challenges are related to data (e.g., volume, lack of structure, noise, heterogeneity and space-time nature), computability (e.g., few algorithms able to handle massive complex data sets) and links to real-time interaction, and visualization methods for exploring fused data.

In her keynote, Dr. Carley defined human terrain as an actionable description of the population, its culture, and its points of influence from a geo-temporal context. Areas of overlap include international affairs, geopolitics, conflict modeling, culture modeling, peacekeeping, humanitarian and relief operations, consumer behavior and dynamic network analysis. A goal of human terrain work is to create operational technologies that allow modeling, simulation, and anticipation of behaviors and activities of both individuals and the organizations to which they belong that are sensitive to the geo-temporal-cultural context (Keller-McNulty et al., 2006). These methods make extensive use of network science and theory. Data comes from text, gazetteers, maps and other sources. Often techniques examine links between elements, such as members of social groups or tribes, or identify critical points in networks, such as sequences of ports-of-call for vessels, or vulnerable points in network traffic (Prietula et al., 1998). Many different visual display methods are used to examine the networks for these points. Challenges stated by Dr. Carley were getting social scientists to use the many available tools, access to geo-tools such as open source geobrowsers, combining spatial and social models, the incompleteness of social data and the lack of a central theory, and the accuracy and reliability of self-reported data.

Working Group Reports

In the working group discussions, research issues of interest included: the integration and fusion of social data, especially given the modifiable area unit problem/ecological fallacy; the lack of accurate GPS point traces on individuals, and hence reliance on census and other data sources; the need to integrate highly disparate data on economy, sociology, transportation, anthropology, ethnicity, religion, culture, and history; and the large differences in data certainty and reliability.

In terms of fusion, challenges identified by the working group participants were integrating data across spatial scales, dealing with semantic interoperability, conflation, dealing with sensors with different resolutions or spatial frameworks, and integrating at the data, information and knowledge levels. Workshop participants also indicated that data fusion needs are still critical in remote sensing, and are complicated by sensor networks. Sensor level fusion, using techniques such as support vector machines and Bayesian modeling seem to be making advances, but the fusion of hard and soft data is still an unsolved problem. The role of humans as agents of data fusion was thought to be in need of study.

Specific topics outlined by the working groups are summarized in Appendix E.

– 3 –
FUTURE RESEARCH AREAS AND IMPLICATIONS

On the third day of the workshop, May 19, 2010, participants focused the results of the earlier discussions into a short list of the research directions they thought would have relevance and value for the National Geospatial Intelligence Agency (NGA). Participants divided into five workgroups, and each group was charged with selecting, justifying and presenting five overarching research themes that had arisen during discussion, drawing from the five core areas or the five cross-cutting themes. Each group formally presented the key themes they selected, and then participants were encouraged to eliminate duplication by grouping the topics when there was substantive overlap. This resulted in the identification of ten future research areas for the NGA (Box 3.1).

Box 3.1
Future Research Challenges for NGA

The ten research challenges, as selected by workshop participants, are:

Visual analytics
Integrating sensors
Human terrain/behavior
Participatory sensing
Improved models of space-time
Development of new paradigms for conveying certainty
Improved geodetic/photogrammetric/remote sensing positioning
Geospatial information retrieval and extraction from text
Database technology and spatial data infrastructure
Geospatial narrative

FUTURE RESEARCH AREAS

Visual Analytics

Visual analytics is defined as the science of analytic reasoning facilitated by the interactive visual interface. Even though this is a new science, the potential to have a positive impact on NGA is significant, moving NGA towards providing highly precise and relevant knowledge products for their stakeholders. Each of the five working groups offered detailed suggestions for developing the science of visual analytics for GEOINT.

The first working group stressed the importance of the development of the science of visual analytics and time-space narratives for geospatial sciences. This group stated that goals need to include optimizing analytical methods, decision cycles, and products through the use of fusion/synthesis, exploiting multi-source, multi-type, temporal and geospatial and dynamic active data and developing new technologies.

The second working group discussed the need to address four topics within visual analytics. These were: (1) to address the cognitive issues through cognitive models of human-computer systems and extending the theory of human computer interaction; (2) to establish methods for evaluation, validation of reasoning, and analysis techniques; and (3) to extend current techniques to address uncertainty, scale, and time series. Lastly, it was thought important to enable mobile, collaborative, and distributed interaction.

The third working group suggested a set of areas specifically for integrative analytics. Their areas included developing four-dimensional space-time representation and analysis techniques, creating methods for dealing with multilevel data, heterogeneity, and uncertainty, and producing algorithms for statistical and machine learning. Interactive analytics were thought critical, that is efficiently coping with massive amounts of information/data, using visualization, haptics, sound, games, and modeling and simulation.

The fourth working group provided ideas surrounding integrated, interactive, and iterative spatial and temporal (visual) analytics. First was the need for dynamic information systems for geospatial intelligence – representation, modeling, and analysis issues—to support workflows and to focus on spatiotemporal data/analysis. Second, methods were desired for social mapping, which is social links and networks, requiring an improvement in the spatiotemporal component of social network analysis, and the identification and representation of dynamic relationships over space and time. Next, the need for true, comprehensive/complete space-time analysis was stressed, to address semantic and space-time scales, using scalable algorithms and infrastructure for large volumes of data. Fourth, means were thought necessary to represent and utilize and analyze data and information quality, reliability, and confidence. This implies the need to determine (1) what information is needed by particular users and determine the appropriate evaluations methods and (2) how to make information on certainty/uncertainty useful and to support reasoning with uncertainty and with heterogeneous kinds of information. Lastly, the group discussed the need to develop adaptive visual analytic methods that support a range of users/uses and a range of devices, across a range of interaction science issues, human-algorithm interaction, speed of response to support interaction, methods to support sensitivity assessment in real time, and uncertainty representation. This led the group to state a need to develop methods to determine what visual and other analytical methods are appropriate for specific problem contexts and how the success (or lack of success) of the methods and tools need to be evaluated.

The fifth working group suggested using visual analytics for geospatial sciences as models for incorporating human analysis (integration of human and computer intelligence), for using collaborative methods, such as social games, and interactive visual analytics, and for communicating salient heterogeneous information to the end users (more effective participatory sensing). This group suggested that important future research included computational modeling, large data organization, modeling, indexing, retrieval, visualizations, analysis and forecasting.

Visual analytics was addressed in many of the other discussions and appears to have broad interdisciplinary impact on geospatial sciences and applications. The European scientific community also sees visual analytics as an important research opportunity, as illustrated by the recent Geospatial Visual Analytics: Focus on Time Workshop and keynote presentation on Visual Simulation at the 13th AGILE International Conference on Geographic Information Science (2010; See: http://www.agile-online.org).

Summary of Working Groups' Discussions on Visual Analytics

- Computational modeling
  - Large data organization, modeling, indexing, retrieval, visualizations, analysis
  - Forecasting

- Models for incorporating human analysis (integration of human and computer intelligence)
  - Using collaborative methods, such as social games, and visual interaction in aid of visual analytics
  - Communicating salient heterogeneous information to the end users (more effective participatory sensing)

- Developing the science of visual analytics for GEOINT
  - Addressing the cognitive issues
    - Cognitive models of human-computer systems
    - Extend theory of human interaction
  - Establish methods for evaluation & validation of reasoning & analysis techniques
  - Extend current techniques to address uncertainty, scale & space/time
  - Include mobile, collaborative, distributed interaction

- Integrative Analytics
  - 4D space-time representation and analysis techniques
  - Multilevel, Heterogeneity, Uncertainty
  - Algorithms: statistical, machine learning
  - Interactive analytics—efficiently coping with massive amounts of information/data
    - Visual, haptic, auditory, etc.
    - Games, computational modeling, simulation

- Integrated, interactive, and iterative spatial and temporal (visual) analytics

  - Dynamic information systems for geospatial intelligence – representation, modeling, and analysis issues; support workflows; focus on spatiotemporal data/analysis;
  - Social mapping, social links and networks – improve spatiotemporal component in social network analysis; identify and represent dynamic relationships over space and time.
  - True, comprehensive/complete space-time analysis does not exist; address semantic and space-time scales; need scalable algorithms for large volumes of data.
  - What is the right infrastructure that deals with reliability and latency associated with massive quantities of data
  - How to represent and utilize/analyze data & information quality / reliability / confidence; Determine what info is needed by particular users and determine the appropriate evaluations methods; How to make info on certainty/uncertainty useful? Supporting reasoning with uncertainty and with heterogeneous kinds of info. What is the right infrastructure that deals with reliability and latency associated with massive quantities of data

- Need to develop adaptive visual analytic methods – that support a range of users/uses and a range of devices, and a range of situations; interaction science issues; Human-algorithm interaction – research issues speed of response to support interaction, methods to support sensitivity assessment in real time; uncertainty representation; Need to develop methods to determine what visual and other analytical methods are appropriate for specific problem contexts and how to evaluate the success (or lack of success) of the methods and tools.

- Development of the science of visual analytics and narrative to optimise analytic methods, decision cycles and products through the use of fusion, synthesis, multi-source, multi-type, temporal and dynamic products + technologies

Integrating Sensors

Emerging sensors, such as hyperspectral and LiDAR, not only will provide additional information, but also, in combination with traditional remotely sensed data (panchromatic electro-optical), enable information derivation not determinable by a single sensor. New and ubiquitous sensors can have many sensing modalities, can be networked, can provide continuously streaming data, and can be miniaturized; they will collect physical features—environmental, motion, chemical, and biological data, etc.—with location information of sensed data, and collect that data with varying degrees of resolution and quality. Sensors are being deployed not only on spaceborne platforms, but also on aerial UAV, drones, vehicles, in-situ, underwater, underground, and on humans, i.e., in backpacks and cell-phones. These sensors and varieties of platforms and modalities require new paradigms and significant research in sensor modeling, sensor calibration, and sensor data fusion as well as new methods to address the complexities of mission planning and adaptation of tasking. Workshop participants expressed the concern that the vast quantities of data collected will require the development of "smarter" processing methods, perhaps coupled and on-board with sensor platforms. Significant research will be required in spatial information generation—automated feature extraction—prompted by the plethora of collection capabilities. Participants also noted the need for the development of ways to integrate data of varying quality, as well as data that is metric and non-metric, with existing geospatial information using prior knowledge and multiple sources of information and knowledge.

Summary of Working Groups' Discussions on Integrating Sensors

- Spatially integrated sensing – across scales, (multiple hierarchy, multiple sources) how does larger scale sat. RS
  - Integrate participant / social data to fill holes
  - Deal with mixed data quality across sensors/sources; security of data sources; credibility
  - Including environmental sensors, etc
    - Surface, sub-surface, atmospheric
  - Change over time integrated in space
  - Exploit hyperspectral imagery
    - Integrate with other data, GIS, etc. to improve understanding of data
    - Exploit other information (culture, context, etc.)
    - Add TIME (as described in photogrammetry)
    - Change dynamics
    - Adaptive sensing

- Improved GEOINT from variety of sensors/platforms, including new platforms (e.g. nanosats, man-portable)
  - Improved algorithms for automation, feature extraction, etc
  - New platform designs, networks
  - Mission planning, sensor modeling, etc
  - New sensor capabilities (new designs, "smart" sensor, hyperspectral, etc)
  - Calibration of sensors
  - Sensor fusion

- Advanced Sensing

- Development of high quality, miniaturized, intelligent sensors
  - Novel sensing modalities: biological and chemical
  - Positioning in new places—underwater, underground, etc.

- New paradigms for calibration
  - Traditional and new sensing modalities

- Automated geospatial feature extraction + knowledge generation from integrated multi-sensor/source metric + non-metric data acquisition systems and prior knowledge

- Heterogeneous spatial data acquisition and analysis
  - Using participatory–sensing/ to leverage geo-spatial data collection
  - Modeling
  - Adaptive sensing, participatory sensing, multi-sensor, multi-platform,
  - Quality Control (Best practices, benchmarking, etc.)
  - Issues of data provenance and privacy

Human Terrain/Behavior

The Human Terrain theme arose in a number of working groups and encompasses using geospatial-based observations for analyzing, algorithmic modeling, and assessing or predicting future social behavior, often in rapidly evolving situations. Workshop participants stated the following as key research areas within human terrain: geospatial data collection techniques for observing human behavior; geospatial integration of social, behavioral and cultural data; and the use of participatory data – policy for acquiring, influencing participation, dealing with security and privacy issues, mixing participatory data with traditional data, assessing reliability or credibility, and understanding cultural and social constraints on participatory data.

Participants also thought research was necessary toward models for human behavior and interaction including individuals, organizations, networks, and communities that include: (1) the importance of social factors (culture, politics, history, economics, etc.); (2) human interaction with their physical environment, and; (3) integration of geospatial, temporal, dynamic social network and socio-cultural factors. Some participants stated that such research can lead to predictive systems that rapidly and accurately convey certainty/reliability of predictions, are transparent both in methodology and sensitivity to input data, and allow rapid assessment and decision making. Also raised as an important issue was the development of standardized, quality data sets for development and testing of new theory and model algorithms.

Summary of Working Groups' Discussions on Human Terrain

- Modeling human behavior
  - Interaction among humans (individuals, organizations, networks, communities)
  - Importance of social factors:
    - Culture, Politics, History, Economics, etc.

- Interaction/relationship of humans with their physical environments

- Development and validation of theoretically informed models

- Geospatial methods to analyze, model, and predict human behavior. We cannot model it; relating social factors to physical factors. e.g., can game theory be spatialized as a method to address this? Integrate methods dealing with human behavior into geospatial analytics. Evidence-based geospatial prediction/simulation for human behavior.

- Geospatial-based integration of social, behavioral, and cultural data (including participatory data) — how to deal with mixed type / mixed quality data (crowd sourced data and sensor data); security-privacy issues – how to influence social media to generate data that is needed; how to gauge credibility, reliability, etc.; knowledge – recognize human behavior, data repository + expertise repository; shared conclusions/findings – collaborative information generation and decision making; participatory expertise; understanding relation of cultural and social factors; guidelines on policy and practice of collection

- Development of data collection techniques, analytics, forecasting, visualisation, service chains + theories that can simultaneously accommodate integrated geospatial, temporal, dynamic social network and socio-cultural factors for rapid social situation assessment.

Participatory Sensing

Workshop participants identified the emerging paradigm of Participatory Sensing as an area of future research investment for the NGA. Instead of relying on unattended autonomous sensors as traditional Remote Sensing and Embedded Sensor Networks do, Participatory Sensing engages individuals, groups, and communities in the act of collecting, analyzing, and disseminating urban, social, and other spatio-temporal information. Ubiquitous wireless data networking and sensor-instrumented mobile smartphones provide the platform on which participants can be engaged for collecting diverse geospatial information, and in ways ranging from voluntary and opportunistic sensing to directed and coordinated sensing campaigns. Human mobility and intelligence enables collection of measurements and contextual information that traditional instruments cannot easily replicate. Recognizing that both the opportunity and the challenge of Participatory Sensing arise from human participation, Many participants identified the following key elements of a research agenda that will enable effective use of Participatory Sensing in GEOINT. The issues are:

- Effectively involving human participants using mobile technologies
  - Methods for planning and optimizing sensing
  - Methods for control and incentivization

- Addressing quality, uncertainty, and trustworthiness of participant-contributed data
  - Methods to cope with human bias, selection bias, competence, sabotage

- Responsibly involving human participants
  - Policy issues
  - Privacy mechanisms

- Integrating unplanned, unstructured participatory sensing data into GEOINT

- Incorporating prior information

Summary of Working Groups' Discussions on Participatory Sensing

- Enable use of participatory sensing for GEOINT
  - Methods for planning & optimization
  - Addressing uncertainty & trust issues
  - Addressing policy & privacy issues
  - Integration & augmentation of unplanned, unstructured participatory data into GEOINT
  - Develop methods of incorporating *a priori* information

- Techniques for incorporating humans in the loop in the collection and processing of data
  - Utilizing volunteers
  - Making use of mobile technologies
  - Issues of quality (human bias, selection bias, competence, sabotage)
  - Mechanisms for control and incentivization

Improved Models of Space-Time

The integration of time and space in GIS and Geospatial Analysis was seen by the workshop participants as key to further the representation and understanding of complex dynamic physical and socio-behavioral processes. This will require the development of new and improved models that integrate the time structure of events, as well as their aggregates and narratives, with the spatial structure. It was noted that formal models for space-time dynamics need to be refined and extended. Crucial in this is a theory of scale dependence in order to handle multiple resolution data bases and the integration of social, cultural and behavioral factors. Related to the theoretical development is the need to represent, communicate and visualize space-time dynamics. Some stated that progress in this direction is necessary in order to move beyond the current largely static conceptualizations and representations.

Summary of Working Groups' Discussions ob Space Time Models

- Improved models of space/time
  - Development of a theory of scale dependence to better understand feature relationships
    - Addressing multiple scale, multiple resolution databases
  - Improved model of time structure (akin to space structure) with events as basic units, aggregation of events, narratives, etc.
  - Integrated space/time structure

- 4D modeling
  - Incorporation of space and time dynamics
  - Incorporation of social, cultural, and behavioural, factors
  - Representation, communication, and visualization of time

Development of New Paradigms for Conveying Certainty

This topic of conveying certainty arose in almost all aspects of working group discussion as a long-term issue across all NGA core areas that requires more robust treatment. As NGA moves from traditional data sources toward more ad hoc and less quantitative data sources, participants stated that renewed or new emphasis is necessary in the following areas: the development of tools for establishing data and information quality at all stages of the information chain from collection to decision making; the creation of methods to establish reliability of participatory data; the development of methods to detect participatory data manipulation; and means to convey reliability in visual data. Broader themes identified by the groups included better understanding human interaction with visual data, how to do statistical and semantic fusion of model source data and information with inherent uncertainties in the observational data and lastly how to characterize uncertainty in relationship to scale and resolution.

Summary of Working Groups' Discussions on Conveying Certainty

- Developing new paradigms for characterizing uncertainty
  - Better methods of representing/visualizing uncertainty
  - Includes reliability, confidence, trust, error, etc.
  - Application to participatory sensing, etc
  - Application to all NGA core areas (geodesy, remote sensing, cartography, etc)
  - Including relationship to scale & resolution

- Quality and Provenance

- Fundamental tools required for establishing data and information quality and provenance at all stages of the information chain

- Statistical and semantic fusion of multi-source data and information with modelling of uncertainties inherent in the data and information (geospatial, text, web, Humint)

Improved geodetic/photogrammetric/remote sensing positioning

The workshop participants noted that remote sensing, geodetic and photogrammetry data will continue to require improved positioning to be used effectively in geospatial intelligence. The requirement for improved positioning is necessary for addressing climatic issues, such as sea level rise and ice sheet changes, earthquake activity, for intelligent transportation, and for high geometric accuracy associated with existing and new sensor data sets. Incorporating improved positioning from additional GNSS/GPS (Global Navigation Satellite Systems/Global Positioning System) constellations of satellites, will allow for improved positioning to millimeter level in real time. Atomic clocks used in GPS will continue to improve in accuracy by orders of magnitude. When satellite positioning data is not available, such as in buildings, underground or underwater, then INS (inertial navigation system) will need to be developed to high accuracy levels. Gyroscopes used to measure or maintain orientation of remote sensing devices will continue to require improved positioning. Some stated that improved gravity models are necessary to determine precise orbits and to reduce orbit errors associated with satellites.

Summary of Working Groups Discussions on Positioning

- Improved geodetic/photogrammetric/remote sensing positioning
  - GNSS
  - INS
  - Gyroscopes
  - Atomic clocks
  - Gravity
  - Geoid

Geospatial Information Retrieval and Extraction from Text

Workshop participants stressed the importance of developing the capability to determine and/or refine geospatial information from text search and retrieval. Methods are needed to use geospatial information to interpret unstructured and semi-structured textual information. More challenging is integrating information from a wide range of sources by anchoring them geospatially and understanding and characterizing the geographic variation of language. Some noted that additional research is required to investigate the combination of techno-social predictive analytics with infrastructure-based sensors in aiding the information retrieval and extraction.

Summary of Working Groups Discussions on Geographic Information Retrieval and Extraction from Text

- How to use existing geospatial ontologies to inform the information extraction process

- How to use formal geographic information (e.g., from mapping databases, remote sensing, etc) to interpret unstructured, semi-structured info.

- A challenge is to integrate info from a wide range of sources and anchor them geospatially.

- Understand the geographic variation of language.

- How to combine technosocial predictive analytics with infrastructure-based sensors; to control sensors

Database Technology & SDI

Participants identified database technology and spatial data infrastructure as another important area of future research investment for the NGA. The challenge arises from the increasing richness, quantity, and diversity (e.g., scale, modality, sources, and quality) of geospatial data and information products. Therefore, the participants state that research is needed to develop database technology and spatial data infrastructures that are capable of handling data that is multi-dimensional, spatially and temporally multi-scale, and multi-source, ranging from authoritative to participatory and public. The database requirements for extremely high spectral and spatial resolution, multimedia imagery and free form text, as integrated over the entire Earth, will continue to challenge most existing data schema and models.

Summary of Working Groups Discussions: Database Technology and Spatial Data Infrastructure

- Research into database technology and SDI to handle multi-scale, multi-dimensional, multi-temporal data of both authoritative and public participatory data over time.

Geospatial Narrative

Many GEOINT workflows from data collection to interpretation can be represented as narratives, or stories, about the data or about the world that the data samples represent. Narrative theory has been well developed in disciplines such as story-writing, film studies and literary studies, and narratives are well known as being effective ways to build associations and activate memory. Many geospatial phenomena—for example tornadoes following a storm front, boats leaving and entering ports, or truck convoys moving from camp to airstrip—also follow sequences, and difference from a known narrative becomes a mechanism by which the normal can be discriminated from the abnormal. A research track in geospatial narrative would focus on how to develop computational narratives within a spatio-temporal database. It would design and build structures that would allow narrative objects of any type (e.g. a hurricane) to be automatically recognized and created, then manipulated for visualization and analysis. This may need multisource data, multi-temporal interpolation and simulation, and visualization. Data could be points, lines, areas or volumes. Outcomes would include descriptions of narrative evolution, the use of narratives in interpretation and analysis, and the ability to test a developing situation against all known similar narratives. For example, as a specific hurricane track develops, its path can be tested for similarity against all known prior hurricane tracks, and so estimates of damage, loss of life, and necessary humanitarian relief can be made from the past instances.

Summary of Working Groups' Discussions on Geospatial Narrative

- How to develop computational narratives – representation structure for narratives in a dynamic database

- Narrative as an object that can be manipulated (production of narrative products at multiple levels of explanation)
- Auto-generation of narratives from multiple sources
- Narrative maps to show evolution of activities.

IMPLICATIONS FOR THE SCIENTIFIC INFRASTRUCTURE

Some discussion was devoted to the implications of these above research themes for scientific infrastructure. In some cases, programs to promote science education and to build research infrastructure exist or are planned, such as the National Science Foundation's (NSF) Office of Cyberinfrastructure and the Defense University Research Instrumentation Program. It was felt that existing academic programs would need to respond strategically to these research challenges, and that doing so would require new centers, resources, faculty and students. The need to protect the existing core areas research programs and the need to take advantage of the fact that graduate education is an increasingly global activity were noted. Some felt that perhaps the greatest challenge is dealing with the increasing need for interdisciplinarity in research and education, since universities and programs also have a degree of intellectual inertia and reluctance to change or adapt to new technology and challenges.

FINAL REMARKS

The workshop examined the five NGA core areas and, in many cases, reaffirmed the importance of these areas for NGA's mission. The first day's presentations and break-out discussions outline some of the potential areas of new research in these fields. However, the cross-cutting themes also suggest that the core areas are in evolutionary flux and that emerging fields, as discussed during the workshop, will need to be tracked and monitored. These new areas emerged clearly from the discussions.

The workshop took place in a spirit of cooperation and collegiality. Each of the core areas and emerging fields was represented by world class experts, and participants were prepared for the meeting and seemed pleased with the level of interdisciplinary interaction. The steering committee felt that the record of the discussions and ideas presented at the workshop figure prominently in this report. From among these discussions, hopefully, ideas for the next generation of research at the NGA can emerge.

– REFERENCES –

Banaei-Kashani, F., Shirani-Mehr, H., Pan, B., Bopp, N., Nocera, L. and Shahabi, C. 2010. GeoSIM: A Geospatial Data Collection System for Participatory Urban Texture Documentation *Bulletin of the Technical Committee on Data Engineering*, 33, 2 40-45.

Bruzzone, L., C. Mingmin, and M. Marconcini. 2006. A Novel Transductive SVM for Semisupervised Classification of Remote-Sensing Images. *IEEE Transactions On Geoscience and Remote Sensing* 44(11):3363-3373.

Chen, X., Lai, Z., Li, W. and Zhang, J. 2009. Some critical issues on airborne LIDAR mapping software in coastal survey *Proceedings, SPIE* 7492, 74920F.

Elwood, S. 2006. Negotiating Knowledge Production: The Everyday Inclusions, Exclusions, and Contraditictions of Participatory GIS Research. *The Professional Geographer* 58(2):197.

Flynn, M.T., M. Pottinger, and P.D. Batchelor. 2010. *Fixing Intel: A Blueprint for Making Intelligence Relevant in Afghanistan*. Washington, D.C.: Center for a New American Security. 26 pp. Available online at *http://govcentral.monster.com/news_feeds/visit?uri=http%3A%2F%2Fwww.cnas.org%2Fnode%2F3927*; accessed 8 July 2010.

Elwood, S. 2008. Volunteered Geographic Information: Future Research Directions Motivated by Critical, Participatory, and Feminist GIS. *GeoJournal* 72(3 & 4):173-183.

Flanagin, A. J., & Metzger, M. J. (2008). The credibility of volunteered geographic information. *GeoJournal* 72, 137-148.

Goodchild, M.F. (2007). Citizens as sensors: the world of volunteered geography. *GeoJournal*, 69(4):211-221.

Hornsby, K. S. and Yuan, M. (eds.). 2008. *Understanding Dynamics of Geographic Domains.* Boca Raton, FL: Taylor and Francis.

IVS, 2006. 4th IVS General Meeting, Conception, Chile, January 9-13, International VLBI Service for Geodesy and Astronomy

Jackson, Q., and D. Landgrebe. 2001. An adaptive classifier design for highdimensional data analysis with a limited training data set, *IEEE Transactions on Geoscience and Remote Sensing* 39(12):2664-2679.

Keller-McNulty, S., Bellman, K. L., Carley, K. M. et al., 2006. *Defense Modeling, Simulation, and Analysis: Meeting the Challenge*, Washington, D.C.: The National Academies Press.

Kellndorfer J. M, Walker, W. S., LaPoint, E., Kirsch, K., Bishop, J. and Fiske, G. 2010. Statistical fusion of lidar, InSAR, and optical remote sensing data for forest stand height characterization: A regional-scale method based on LVIS, SRTM, Landsat ETM plus , and ancillary data sets. *Journal of Geophysical Research-Biogeosciences*. 115, G00E08.

Liggins, M., E. Hall, D. L., and Llinas, J. 2009. Handbook of Multisensor Data Fusion: Theory and Practice. 2ed. The Electrical Engineering and Applied Signal Processing Series. Boca Raton, Fla.: CRC Press.

Mingmin, C., and L. Bruzzone. 2007. Semisupervised Classification of Hyperspectral Images by SVMs Optimized in the Primal. *IEEE Transactions On Geoscience and Remote Sensing* 45(6):1870-1880.

Muñoz, A. and Gonzalez, J. 2008. Functional Learning of Kernels for Information Fusion Purposes. *Lecture Notes in Computer Science,* Volume 5197, Progress in Pattern Recognition, Image Analysis and Applications, Springer Berlin / Heidelberg.

National Research Council (NRC). 1985. *Geodesy: A Look to the Future*. Washington, D.C.: National Academy Press.

NRC. 2006. *Priorities for GEOINT Research at the National Geospatial-Intelligence Agency*, Washington, D.C.: The National Academies Press, 102 pp.

Plag, H.-P. and M. Pearlman (eds). 2009. *Global Geodetic Observing Systems: Meeting the Requirements of a Global Society on a Changing Planet in 2020*. Dordrecht, The Netherlands: Springer.

Pultar, E., Cova, T. J., Yuan, M. And Goodchild, M. F. 2010. EDGIS: a dynamics GIS based on space time points. *International Journal of Geographic Information Science* 24(3):329-346.

Prietula, M. J., Carley, K. M. and Gasser, L. (eds.). 1998. *Simulating Organizations: Computational Models of Institutions and Groups*, Menlo Park, Calif.: AAAI Press / The MIT Press.

Roweis, S.T. and L.K. Saul. 2000. Nonlinear dimensionality reduction by locally linear embedding. *Science* 290(5500):2323-2326.

Sanso, F., 2003. A Window on the Future of Geodesy. *International Association of Geodesy Symposia*, Volume 128. Sapporo, Japan, June 30-July 11, 2003.

Schölkopf, B. 1998. SVMs - a practical consequence of learning theory. *IEEE Intelligent Systems* 13(4):18-21.

Sieber, R. 2006. Public Participation and Geographic Information Systems: A Literature Review and Framework. *Annals of the American Association of Geographers* 96(3):491-507.

Telea, A. 2009. Introduction to the special issue of selected papers from SOFTVIS'2008. *Information Visualization* 8(2):85-86.

Tenenbaum, J.B., V. deSilva, and J. C. Langford. 2000. A global geometric framework for nonlinear dimensionality reduction. *Science* 290(5500):2319-2323.

Thomas, J.J. and K.A. Cook (eds.) 2005. Illuminating the Path: The Research and Developm*ent Agenda for Visual Analytics.* Los Alamitos, Calif.: Wiley IEEE Computer Society Press.

Tulluch, D., 2008. Public Participation GIS (PPGIS), in K. Kemp (Ed.) *Encyclopedia of GIS*. Sage Publications, p. 351-353.

van den Hout, A., and I. Alberink. 2010. A hierarchical model for body height estimation in images. *Forensic Science International* 197(1-3):48-53.

Wanninger, L. 2008. Innovation: The Future is Now. Insights with Richard Langley. *GPS World* 19(7):42-48.

Whitten, C. A. 1963. Future of Geodesy. *Bulletin Géodésique of the International Association of Geodesy* 70(1 December).
Xiong, Z. and Zhang, Y. 2010 A critical review of image registration methods. *International Journal of Image and Data Fusion* 1(2):137-158.

– APPENDIX A –
BIOGRAPHICAL SKETCHES OF STEERING COMMITTEE

Keith C. Clarke is a research cartographer and professor in the Geography Department at the University of California, Santa Barbara. He is also the Santa Barbara Director of the National Center for Geographic Information and Analysis. Prior to joining the faculty in 1996, he was a professor at Hunter College and he also spent a year as an advisor to the Office of Research in the U.S. Geological Survey's National Mapping Division. Dr. Clarke's research focuses on environmental simulation modeling, modeling urban growth, terrain mapping and analysis, and the history of satellite surveillance. He has had numerous leadership roles, including president of the Cartographic and Geographic Information Society, and chair of several NRC committees, including one that identified priorities for geospatial intelligence research at the National Geospatial-Intelligence Agency. He currently chairs the NRC Mapping Science Committee. Dr. Clark is a recipient of the John Wesley Powell Award, the USGS's highest award for achievement, and a fellow of the American Congress on Surveying and Mapping. He holds a B.A. from Middlesex Polytechnic (London) and an M.A. and Ph.D. in analytical cartography from the University of Michigan.

Luc E. Anselin is Foundation Professor of Geographical Sciences and the founding director of the School of Geographical Sciences at Arizona State University. He is also the founding director of the university's GeoDa Center for Geospatial Analysis and Computation. Dr. Anselin's research focuses on spatial data analysis and geographic information science, with application to regional and environmental economics, epidemiology, criminology, and political science. He has also worked on information technology challenges for secure access to confidential data. He is a member of the NRC's Mapping Science Committee. Dr. Anselin was awarded the Walter Isard Award in 2005 and the William Alonso Memorial Prize in 2006 for significant contributions to the field of regional science. He is a fellow of the Regional Science Association International and a member of the National Academy of Sciences. He holds a B.S. and M.A. from the Free University of Brussels, and an M.A. and Ph.D. in regional science from Cornell University.

Annette J. Krygiel is an independent consultant on topics such as intelligence strategies, capabilities, experimentation, and applications. Prior to starting her own business, she spent 38 years in the Department of Defense, where she managed geodetic and gravimetric programs and large-scale systems, as well as the development of computer science and telecommunications applications for mapping. She also served as the chief scientist of the Defense Mapping Agency and director of the Central Imagery Office, which were eventually merged with other imagery and mapping agencies into the National Geospatial-Intelligence Agency. Dr. Krygiel has received many awards for her accomplishments, including the Distinguished Civilian Service Award from the Secretary of Defense and the National Intelligence Distinguished Service Medal from the Director of Central Intelligence. She has served on several NRC committees related to defense and geospatial data issues. She received a B.S. in mathematics from St. Louis University and a Ph.D. in computer science from Washington University.

Carolyn J. Merry is a professor and chair of the Department of Civil and Environmental Engineering and Geodetic Science at Ohio State University. She also directs the university's Center for Mapping. Prior to joining the faculty, she held research positions at the U.S. Army Cold Regions Research and Engineering Laboratory and NASA Goddard Space Flight Center. Dr. Merry's research interests are in land cover change and water quality mapping using satellite imagery, watershed and water quality engineering models, and geographic information systems. Her work has been recognized in awards by the American Meteorological Society, NASA, and American Society for Photogrammetry and Remote Sensing (ASPRS). She is a member of the NRC Mapping Science Committee and president elect of ASPRS. She received a B.S. from Edinboro State College, an M.A. from Dartmouth College, and a Ph.D. in civil engineering from the University of Maryland.

Scott A. Sandgathe is a principal meteorologist in the Applied Physics Laboratory at the University of Washington. He is a retired Navy Commander and has served as the Deputy Director of the Joint Typhoon Warning Center and onboard the USS Carl Vinson providing meteorological and oceanographic support for battle group operations. In addition, he has held a number of positions related to research policy and planning in the Navy, including Team Leader for the Office of Naval Research Marine Meteorology and Atmospheric Effects Program. He is currently Technical Lead for the NOAA-Navy-Air Force National Unified Operational Prediction Capability Program. Dr. Sandgathe's research focuses on tropical meteorology, synoptic analysis and forecasting, and numerical weather prediction. He is also developing automated forecast verification techniques for mesoscale numerical weather prediction. Dr. Sandgathe is a fellow of the American Meteorological Society and a member of the NRC Panel of Atmosphere, Climate and Security, under the Committee on Climate, Energy, and National Security. He received a B.S. in physics and meteorology from Oregon State University and a Ph.D. in meteorology and oceanography from the Naval Postgraduate School.

Mani Srivastava is a professor in both the Electrical Engineering and Computer Science departments at the University of California, Los Angeles. He is also systems area co-lead and a research executive committee member at the Center of Embedded Networked Sensing, an NSF Science & Technology Center. Prior to joining the faculty in 1996, he worked on mobile and wireless networking at AT&T/Lucent Bell Labs. His research focuses on power and energy-aware wireless communication and computing systems, wireless embedded sensor and actuator networks, distributed embedded systems, and pervasive sensing and computing. Dr. Srivastava has organized a number of conferences and workshops on these issues, most recently a 2009 NSF Workshop on Future Directions in Networked Sensing Systems: Fundamentals and

Applications. He is also a co-inventor on 5 U.S. patents in the general area of wireless networking. Dr. Srivastava is a fellow of the Institute of Electrical and Electronics Engineers. He received a B.Tech. in electrical engineering from the Indian Institute of Technology, and an M.S. and Ph.D. in electrical engineering and computer sciences from the University of California, Berkeley.

James J. Thomas is a Laboratory Fellow at Pacific Northwest National Laboratory as well as the founder and past director of the Department of Homeland Security's National Visualization and Analytics Center. Mr. Thomas specializes in the research, design, and implementation of information and scientific visualization, multimedia, and human-computer interaction technology. More recently he has led teams in text, numerical, image and video, temporal, and geospatial analysis for massive information spaces. He was named one of the top 100 scientific innovators by Science Digest and twice the Research and Development's Industrial Research top 100 innovators in science and industry. In 2009, he received the Christopher Columbus Fellowship Foundation Homeland Security Award for outstanding scientific achievements in founding and establishing the growing science of visual analytics and the numerous associated technologies that aid in detecting, predicting, preventing, and responding to acts of terrorism. Mr. Thomas chairs the steering committee for the IEEE Visual Analytics Science and Technology Symposium, and is a member of IEEE's Technical Committee on Visualization and Graphics. He is a fellow of the American Association for the Advancement of Science. He received his M.S. in computer science from Washington State University.

– APPENDIX B –
PRESENTERS TO THE WORKSHOP

May 17-19, 2010

Geospatially Enabled Network Analysis
Kathleen Carley, Carnegie Mellon
Advanced Sensors and Information Extraction: Synergies for Optical Sensing
Melba Crawford, Purdue University
Proactive and Predictive Visual Analytics
Dave Ebert, Purdue University
Spatial Information Extraction from Imagery: Recent Trends in Geomatics
Clive Fraser, University of Melbourne
Cartographic Research in the United States: Current Trends and Future Directions
Robert McMaster, University of Minnesota
Data and Visual Analytics for Information Fusion
Haesun Park, Georgia Tech
Technosocial Predictive Analysis: Bridging the Gap between Human Judgment and Machine Reasoning
Antonio Sanfillipo, Pacific Northwest National Laboratory
Participatory Urban Data Collection: Planning and Optimization
Cyrus Shahabi, University of Southern California
An Optimist's 20-Year Look-ahead at Geodesy and Geophysics
Dru Smith, NOAA NGS
National Geospatial-Intelligence Agency
Greg Smith, National Geospatial-Intelligence Agency
GIS as Geospatial Inspiration
May Yuan, University of Oklahoma

– APPENDIX C –
WORKSHOP PARTICIPANTS

Luc Anselin
Arizona State University

Dick Berg
MITRE

Kathleen Carley
Carnegie Mellon

Keith Clarke
University of California, Santa Barbara

Russ Congalton
University of New Hampshire

Melba Crawford
Purdue University

Ralph Dubayah
University of Maryland

Dave Ebert
Purdue University

Eric Edkin
National Research Council

Clive Fraser
University of Melbourne

Ayman Habib
University of Calgary

Mike Jackson
University of Nottingham

Annette Krygiel
Independent Consultan

Alfred Leick
University of Maine

Doug Lemon
Utah State University

Anne Linn
National Research Council

Huan Liu
Arizona State University

Jim Llinas
SUNY Buffalo

Alan MacEachren
Penn State University

Mahendra Mallick
Georgia Tech

Bob McMaster
University of Minnesota

Dean Merchant
Ohio State University

Carolyn Merry
Ohio State University

Alan Murray
Arizona State University

Jason Ortego
National Research Council

Haesun Park
Georgia Tech

Mike Peterson
University of Nebraska

Bill Ribarsky
University of North Carolina

Chris Rizos
University of New South Wales, Australia

Scott Sandgathe
University of Washington

Antonio Sanfilippo
Pacific Northwest National Laboratory

Cyrus Shahabi
University of Southern California

Lea Shanley
National Research Council

Dru Smith
NOAA NGS

Greg Smith
National Geospatial-Intelligence Agency

Mani Srivastava
University of California, Los Angeles

Kay Sullivan
RAND

Hanlin Tang
RAND

James Thomas
Pacific Northwest National Laboratory

Amitabh Varshney
University of Maryland

Joseph Young
Southern Illinois University

May Yuan
University of Oklahoma

Michael Zink
University of Massachusetts

Michael Zyda
University of Southern California

– APPENDIX D –
WORKSHOP AGENDA

Workshop on New Research Directions for the National Geospatial-Intelligence Agency
Keck Center
500 Fifth Street, NW, Washington, D.C.
May 17-19, 2010

Agenda

Tuesday, May 18, Room 109

8:00 Continental breakfast available

8:30 Overview of plans for the day — *Keith Clarke*

Plenary session V: Cross cutting themes (*20 minutes each*)

Forecasting: "Technosocial Predictive Analysis: Bridging the Gap between Human Judgment and Machine Reasoning" — *Antonio Sanfillipo, PNNL*

Participatory sensing: "Participatory Urban Data Collection: Planning and Optimization" — *Cyrus Shahabi, U Southern California*

Visual Analytics: "Proactive and Predictive Visual Analytics" — *Dave Ebert, Purdue*

10:00 Instructions to the working groups and break — *Keith Clarke*
- Other ideas not raised in the presentations
- How do advances in the cross-cutting themes shape the 5 core areas?

10:30 Working groups on forecasting, participatory sensing, and visual analytics

Working group 1, *Room 109*

Carolyn Merry (chair) and Michael Zyda (vice chair)
Working group 2, *Room 202*
Luc Anselin (chair) and Bill Ribarsky (vice chair)
Working group 3, *Room 208*
Mani Srivastava (chair) and Amitabh Varshney (vice chair)
Working group 4, *Room 213*
Scott Sandgathe (chair) and Mike Jackson (vice chair)
Working group 5, *Room 600*
Jim Thomas (chair) and Michael Zink (vice chair)

12:00 Working lunch

1:00 Plenary session VI: Cross cutting themes (*20 minutes each*)

Beyond fusion: "Data and Visual Analytics for Information Fusion" — *Haesun Park, Georgia Tech*

Human terrain: "Geospatially Enabled Network Analysis" — *Kathleen Carley, Carnegie Mellon*

2:00 Instructions to the working groups — *K. Clarke*

- Other ideas not raised in the presentations
- How do advances in the cross-cutting themes shape the 5 core areas?

Working groups on beyond fusion and human terrain

Working group 1, *Room 109*
Carolyn Merry (chair) and Huan Liu (vice chair)
Working group 2, *Room 202*
Luc Anselin (chair) and May Yuan (vice chair)
Working group 3, *Room 208*
Mani Srivastava (chair) and Jim Llinas (vice chair)
Working group 4, *Room 213*
Scott Sandgathe (chair) and Mahendra Mallick (vice chair)
Working group 5, *Room 600*
Jim Thomas (chair) and Joseph Young (vice chair)

3:30 Working groups prepare reports

4:00 Plenary session VII: Working group reports (*5 minutes each*)

Forecasting, participatory sensing, and visual analytics
Working group 1 — *Michael Zyda*
Working group 2 — *Bill Ribarsky*
Working group 3 — *Amitabh Varshney*

Working group 4	*Mike Jackson*
Working group 5	*Michael Zink*
Beyond fusion and human terrain	
Working group 6	*Huan Liu*
Working group 7	*May Yuan*
Working group 8	*Jim Llinas*
Working group 9	*Mahendra Mallick*
Working group 10	*Joseph Young*
Discussion	*All*

5:00 Workshop adjourns for the day

– APPENDIX E –
WORK GROUPS – FIRST TWO DAYS:
RESEARCH TOPIC NOTES

Photogrammetry

- Go to 4-D space-time maps and ability to search and analyze for events and scenarios
- Use multi-sensor (cameras, sound) and IMUs on people to do internal mapping of buildings in real time (fire fighters; soldiers)
- Develop situationally aware tools: need to have products and analysis tools suited to the purpose.
- Analytic Integration:
    - Using photogrammetry in the aid of social intelligence: (e.g., automated personal identification, crowd estimation, automatic generation of searchable maps)
    - Use of interactive systems, including gaming, needs to be leveraged by the geo-spatial science in a whole different level to support decision science
- Need to move away from four traditional NGA core areas
- Blending of computer sciences, statistics, electrical and computer engineering, geodesy, geography, bioinformatics
- Integration of Uncertainty/Error into Sensor Models and Analysis
    - Characterize multiple sources of uncertainty
    - Sensor errors
    - Confidence in data (subjective sources)
    - Models (Empirical vs physics based)
    - Utilize advanced statistical estimation, numerical methods, optimization
- Adopt new strategies to address complex problems
    - Interdisciplinary
    - Multiscale/multiresolution data integration and analysis
    - More effective use of human in the loop
- Leverage consumer photogrammetry & merge metric/non-metric technologies
- Merge traditional & non-traditional sensing methodologies (kinematic, participatory networks, social media, surveillance networks)

Remote Sensing

- Exploit hyperspectral imagery
  - Integrate with other data, GIS, etc.
  - Add time (as described in photogrammetry)
  - Exploit other information (culture, context, etc.)
- Adaptive sensing (real-time) based on info value of sensor
- Link the above with text info to aid classification and event and scenario recognition; link with visual analytics.
- Exploit atmospheric impacts as signals
- Uses networks of "small satellites" to gain distributed data
- Adapt products, tools to end user (first responder, soldier, analyst, etc.)
- Emphasize multi-sensor fusion/information extraction
  - Decrease uncertainty
  - Exploit redundant capabilities
- Greater utilization of state-of the art algorithms
  - Estimation theory – statistics and electrical engineering
  - Robust nonlinear optimization – numerical analysis
  - Statistical sensor measurement models - Nonlinear filtering
  - Advanced software – Object oriented C++
- Coordination with other government agencies
  - DARPA, AF, Army, Navy
- Exploitation of knowledge sources beyond image data mining; make relevant knowledge sources available; knowledge-based classification
- Enhance change analysis – beyond the process of measurement & classification to dynamics, behavior, and prediction (issue of sensor control/tasking)
- Need more than just the inanimate landscape, but also the dynamic, social environment (e.g. the flux of a living city) = GEOINT
- Metadata and Tagging – Key for fusion; Relate to other non-GeoInt sources (semantic /tagging interoperability challenge)
- Augmenting the image analyst –more tools, knowledge, visual analytics, automation, mining given a specific remote sensor
- Infrastructure implications – data storage/distribution/throughput to the analyst
  - Remote sensing: We have lots of data (increased availability of commercially collected data) – Can we analyze this data?
  - Data collection agency, Delivering tools for data analysis (multi-resolution, multi-sensor, multi-platform, multi-temporal, current and future sensor technologies – including new sensors that are not fully understood)

Cross-Cutting Issues

- Data: bring processing closer to the data acquisition system (selective provision of data)
- How to incorporate 3rd party data/information into NGA processes (reliability, metadata, etc)
- Need more comprehensive metadata
- Processing to support near-real time processing of constant data streams from drones/uavs

- Need to blur processing distinctions between satellite, aerial & terrestrial data acquisition systems
- Quality of Information
    - reliability/integrity of automatically generated spatial information
    - scaleability
    - more comprehensive use of supporting information (e.g. environmental)
- Quality Assurance: System calibration, mission planning for different applications
- Quality Control: verifying the quality of the different products at different levels (sensors, data, information, and knowledge)
    - Develop test sets for different products
- Blending of information:
    - Interface across different information types
    - Information fusion (integration of open source information – quality control of information – evaluating the reliability of this information)
- Information/Data Presentation
    - how to compress petabytes of data to kb of information for presentation to the end-user
    - supporting information needs to be more fully utilised

Automation:
- Is full automation possible and do we need full automation? (reliability issue)
- Provide increased human support to carry specific tasks
    - For example: Tuning the learning models (more of an art that relies on the expertise of the operator ◊ reducing the level of expertise required
- Modeling and data processing:
    - Modeling of non-traditional and emerging sensors (e.g., DSLR, flash LiDAR, range cameras, etc.)
    - Data, information, to knowledge transformation
    - High resolution versus low resolution – Local versus global coverage – Smart Sampling of the landscape
    - Considering the time dimension in geo-spatial data analysis (e.g., Pattern of life assessment)
- Fusion
    - Models for determining the optimal sensors/data needed for deriving desired information (requires data repository that have been geometrically, radiometrically, stochastically checked/pre-processed)
    - Information fusion: facial reconstruction, CV
    - Evaluate the results (how it relates to the end goal), understanding the data

Cartographic Science
- Multi-scale to continuous scale maps
    - Beyond tile-based mapping, beyond Mercator projection
- Improve speed of map presentation
    - Multiple scale levels / all scales
- Interactive cartography driven by eye tracking, brain sensing, other body sensors
- Beyond cartographic scale

    - Investigate semantic aspects of scale
    - Represent human activity at multiple temporal scales
- Need timely access to geoint at differing scales based on differing user tasks
- Incorporation of volunteered geographic info
- Social "mapping", in space/time in addition to physical objects/terrain… research challenges? Social links/networks have geospatial characteristics, how to deal with them in a spatial sense? … have to interface with other types (agencies) of "INT"
- Address challenge of how to visually present data & information quality / reliability / confidence;
- Determine what info is needed by particular users and determine the appropriate evaluations methods

Geodesy

- Integration of GPS in all aspects of geospatial technology.
    - applications still in infancy
- Increase proficiency in use/interpretation of GPS positioning
    - Provide means of assurance that people using GPS for particular tasks know what they are doing
- Ubiquitous GPS
    - Integration of multiple receivers; phone, navigation
- Expansion of continuously operated reference system (ground-based) – CORS
- Geodesy does not deal with humans directly (classical defn.), but gives information that supports societal & scientific needs… but reference frame is "invisible"
- Impressive progress in geodetic accuracy… but how to "operationalise" geodesy missions & services? What should NGA do? GPS/GNSS used in many positioning apps… could we cope without it? What about difficult environments where GNSS doesn't work?
- Establish a geodetic reference frame at sub-millimeter level; research needed at observational level; drives high performance computing research, et al
- Next generation of positioning instrumentation and inertial navigation systems stable to the centimeter level over time
- Geophysics: collaborative research, could be informative to NGA (in terms of data)
- Application oriented datum; provide transformation
- Gravimetry: UAVs; time dependent gravity; GRACE mission

GIS and Geospatial Analysis

- Continue to pursue temporal dimension
- True, comprehensive/complete space-time GIS/geospatial analysis does not exist.
- Expand the narrative
    - Geospatial discourse constrains possible tasks
    - Restricted GIS vocabulary to communicate tasks
    - Production of narrative products at multiple levels of explanation
- Incorporation of volunteered geo-information
    - Rating system for accuracy
- Need to understand how to work with the narrative framework

- Need to achieve timely automated extraction; Need OO software approach
- Automated Service and workflow discovery to enable automatic tool application

- Conceptualize complex information into story line

- Communication of geo-spatial issues
  - static and dynamic communication of narratives
  - visualization of narratives

<u>Cross-Cutting Issues</u>

- Are the core NGA areas “stovepipes”? Are they the right ones?
- How do people respond / perceive / trust quality statements, esp. for large amounts of data

- Need integration of geo information from unstructured sources (text), physical domain, social domain, and knowledge domain with geoint;

- Use Game based analytics: explore data set in terms of games; analyze game strategy/pattern; use information for interview techniques

- Cognitive effectiveness of geo-spatial technology
  - brain scans, MRI, eye/scan patterns, etc.
    - Logical
    - Physical

- Broader cross training of students in geo-spatial workforce … computer science, behavior, …
  - understanding … geophysics, geodesy, …
  - facilitating interdisciplinary training and research

Working Groups: Research Topic Summary

<u>Forecasting</u>

- Challenges
  - Predicting human behavior - relating social factors to physical factors. Geospatial elements need to become part of social network theory.
  - No grand unified social science theory. There are multiple theories from many different parts of the social sciences.
  - Low-hanging fruit - Gross human behavior may be predictable to some level.
  - More study required on foundational framework of social science integration with geospatial data.
  - Rare events - perhaps some focus on predicting the unpredictable.
- Spatial data analysis methods need to be incorporated to get better predictions that put in spatial relationships and meaning.
- Need to tie together of spatial data and temporal forecasting.

- What are the validation methods? Need to develop general validation approaches. Need sensitivity analysis.
- Should we distinguish between prediction and forecasting? Be sure that all aspects of these areas are being covered.
- The forefront of modeling. More complex models that are combinations of very different models for actionable results.
- Technosocial Predictive Analytics
  - Interesting interplay between social networks and physical infrastructure
  - Needs systematic work on defining priors
    - Black Swans are a challenge since not enough data on extreme events
  - Needs Visual Analytics as a visual tool to gain better insights
  - Links possible with GeoCollaboration
    - Collaboration over time, space, expertise
  - Beginnings of applying computing to sociology and anthropology exciting!
- Modelling of human behaviour – more interactive and real - time forecasting tools where problem domain is constantly changing. Use of normality modelling and anomaly detection as alternative to deductive based forecasting.
- Computational modeling, prediction, and analysis are important research topics for the future
  - Potential to guide data collection/assimilation

Participatory Sensing

- Uneven distribution of sensed data.
- Privacy issues
- Crowd sourced data aggregation methods need to be developed.
- Understanding when crowd sourcing is useful.
- A very powerful way of collecting GIS data.
- What about foreign countries or areas where you can't apply your structure? "Unstructured collection". Need on-the-fly planning.
- Use the GIS as a framework. May already have some 3D models, images, etc.
- Building shared spatial knowledge bases with participatory input and sharing. Active knowledge bases.
- Directed planning; opportunistic planning. Situationally aware models. Need to get actionable results. Spatio-temporal models of social, political dynamics.
- Trust and confidence; how to account for biases and keep this info with collected data. How to do quality control in a messy data environment. This needs new ideas.
- Add reference data (reference models?) as points of validation with data of uncertain accuracy and provenance. This could be a general approach.
- Embed social networking in spatial-temporal. Insert the idea of locality and spatial structure in social network analyses.
- Quality control
  - Need methods to aggregate measures of quality
  - Timeliness is an important dimension
  - Measures of trust, reliability, provenance: don't trust; verify
  - Spot-checking with high-quality, calibrated sensors to improve trust and quality

- Judicious use and context of information collected
    - Eg: owner-defined property lines / conditions valuable in non-legal contexts
- Systematic approaches to integrate information from multiple sources:
    - Domain knowledge/expertise such as local context (cultural)
    - Participatory Data Analysis – Wikipedia over GIS
    - Counter-point to the deep/intensive thinking of the analyst
- How to engage all relevant sub-groups (age, sex, socio-economic) in participatory data collection?
- Develop the wider model against which participatory data can be tested. Use of prior knowledge for improved registration and classification
- Understanding of the quality compromises and strengths of having mixed use of authoritive and public participatory data – requires broader development of the models of use.
- Understanding the relationship of culture and social factors to policy and practise of collection + use of public participatory data. Research into security issues of participatory data.
- Participatory sensing: Integration is important!
    - How to influence social media to generate data that is needed?
    - Research to calibrate and judge quality of sensor in participatory sensing to allow decision making
    - Data fusion from this data with serious geo information?

Visual Analytics

- Specific interfaces for specific users? Emphasize the generalization. What are the underlying fundamentals.
- How to get from visualization to underlying methods? Need to have understanding of domain areas. Can general principles be extracted?
- Developing a repeatable body of knowledge within visual analytics eg generic rules applying to the interpretation of data. Develop evaluation criteria.
- Interactive part of visual analytics is a key aspect of its contribution here.
- Integrated tools. Integrated, iterative, interactive—this is the new thing that visual analytics can bring, even using existing analysis tools. (NO TOOLKITS).
- New ideas derived by looking at aggregates. Individual locations to aggregations that make sense for groups. Functional and meaningful scales and multiresolution methods. Attach meaning to aggregations. Space/time aggregations.
- Visual is not the only sense as you only reach a small part of the population (19%).
- Interactive analytics is may be the right term
- Metaphors for interaction with models & animations need to be developed.
- Integrated spatial & temporal analytics
- Understanding the use of animation
- Modeling, simulation & high performance computing
- Proper depiction of data quality & error uncertainties
- Games
- Social interactivity
- Importance of design & art as an additional skill to be embraced.

- Workflow
- Domain-driven integration of information from multiple sources
  - Take advantage of human cognitive abilities
- Need to address how techniques work across scales
  - agent-based approaches, links, …
- Need new advances in interaction for visual analytics
- Further strengthen bridges between Visual Analytics and other areas
- Visual narratives
  - Causality
- Quality of the visualization
  - Develop techniques to measure quality of the presentations
  - Minimizing unintended artifacts, illusions, confounds, etc.
- Visualising / communicating uncertainty. Development of interactive visualisation tools - dynamic feed-back with analyst through eye-tracking and other sensors.
- Collaborative two-way participatory augmented reality.
- Achieving the correct balance between full automation and visual analytics assisted decision making – how to decide which to use in specific situations?
- Computational modeling and/or visual analytics
  - How to enable human reasoning with large amounts of heterogeneous geospatial data?
  - Data fusion
  - Deal with users
- Science of interaction: Need to develop adaptive visual analytical methods to support geospatial users.

Beyond Fusion

- Data Fusion
  - Relate to geo-space:
    - Represent spatial and non-spatial dimensions
    - Incorporate spatial structure: spatial variation or spatial correlation
    - Couple spatial and non-spatial algorithms
    - time dimension?
  - Vector space and graph space; opportunities to integrate or couple? Cross-correlate outcomes? How to represent and handle uncertainty?
- Different forms of spatial data
  - High-resolution, attributes cross space
  - Location (point or area), boundary, space of different scales
  - Models
  - Best way to combine GIS data layers, coding, incorporating uncertainty
- Non-spatial data fusion (as in Haesun Park's talk): cognitive domain
  - Cognitive aspects of knowledge fusion
- Fusion challenges
  - Scale
  - Semantic interoperability
  - Different resolutions
  - Fusion at different levels (data , information, and knowledge)

- Heterogeneous data of different fields/kinds of knowledge, disparate terms/understanding
- GPS positioning
  - Data on positioning and gravity are uncorrelated, nicely separated
  - 2-, 3-, 4-d geodesy, not much to gain from data fusion
  - Essentially, it's about data understanding
- Fusion has a lot to achieve, let alone beyond fusion
  - Is it the same as merging? Conflation is part of fusion.
  - Need for clarification, vocabulary, a scientific language
- Can disparate data/information/knowledge be put together? Redcross, trusted feedback, outdated geospatial data together
  - Would techniques presented take care of these
  - Overarching issue of uncertainty labeling for broad NGA data set needs to be addressed; what is uncertainty of high-dimensional data?
- A set of techniques for understanding relations in high-dimensional data
    - See also Manifolds, etc.
    - Applications to GI data not shown
    - Loss of visibility of Space and Time at "preferred" scales
- Powerful, but evaluation methods need to be developed
- Do not stand alone—insight needs to be developed alongside
  - Analyst Interaction important
- Also need methods to understand large disparate data bases
  - Interrelationships possibly not understood
- Both Broader understanding and uncertainty reduction will likely require complementary, non-GI data
- Comparison of fusion algorithms from visual analytics with existing fusion algorithms
- Early fusion, mid fusion, late fusion
- Bayesian fusion algorithms
- Hard-soft fusion using hard sensor data and text, human generated, web derived information
- Compare and evaluate the accuracy and applicability of these two types of fusion algorithms
- Need scalable algorithms to handle large volumes of data in real-time and interactive mode
- Would approximate, but faster algorithms be desirable?
- Need to develop systematic approaches to matching computationally driven interfaces to user work practice
- Need to investigate existing standards such as the Predictive Model Markup Language (PMML) to use the same data for different classification algorithms.
- How to retrieve geospatial documents and extract geospatial information from text is still a challenge
- How to use existing geospatial ontologies to inform the information extraction process
- How to enable human computer interaction when complex modeling is involved
- Develop methodology to create heterogeneous benchmark data sets for research
- Formulation of standards for methodology and data structures

Human Terrain

- Human Landscape is a better term – Human condition, biophysical conditions
    - Economy, sociology, transportation, anthropological, ethnic, religious, cultural, historical
- Geospatial, social, cultural data integration and analysis
    - More systematic approaches in collection, coding, displaying, understanding
    - Categorizing trivial and non-trivial data
    - Voluntary and non-voluntary contributors may not be aware of the consequence of making data available
- Data uncertainty, quality, consistency, reliability, disparity, fuzzy
    - Tools to filter and clean up data
    - Identify what data is necessary for a given task
- Collaborative tools for crowd-source data
    - Interactive tools
- Proper analysts with specialized knowledge
    - Human intervention to double check the quality (human in the loop)
- Human Terrain
    - Relate analytical outcome based on the significance of consequences of prediction errors; should we weight the outcomes accordingly?
    - Assess possibility or level of confidence on data and analytical outcomes
    - Interoperability: customized system vs. open system; closed sourced black box? scalability? Need to consider modularized system and develop API to couple with other systems
    - Need a stronger geospatial component in social network analysis; dynamic relationships over space and time,
    - Social networks in virtual space vs. in physical world
- Cross-cutting
    - Complexity of analysis: ability to interpret the results
    - Absolute single result vs. multiple possible outcomes; means to assess and communicate uncertainty in decision support
    - Develop an architecture for supervisory level model analysis that combines outcomes from multiple models to mediate meaningful and coherent advice
        - Historical studies: run models against historical/past data
        - Compare outcomes from multiple models
    - Differential uses of words or dialects in different places,
        - how to understand how people use language in the context of place (place-dependent use of words or phrases);
        - identify clues used in a language, relate the outcome in an analytical manner back to the spatial context (to know where the communication took place)
- Methods to enable analysis in native language
- Human Terrain-based Dynamic Network Analysis seems to serve well as one basis for structuring a broad range of social phenomenology in space-time.
    - Representation and Visualization in GI space an issue
- Quality assertion, quantification an issue

    - Highly disparate underlying data quality levels; need agreed ontology
    - NGA to develop technical and ethical best practices for collection?
    - Interplay between Space/Time accuracy and relational accuracies
    - Deception possible, not easy to detect
- A form of "Narrative"? Perhaps useful to assess commonalities, distinctions in these methods
- A larger issue lurking here?: methodological synthesis to deal with the space-time dynamic
-

Cross-Cutting Issues

- Computation (cloud computing, mobile computing, analytical servers)
- Distribution of data/data storage
- Customization of products—making dynamic products for end users to dissect, modify, traceability of evidence and logic (case files FBI/doctors)
- Validation, data quality, spatial uncertainty
    - Populist info: Privacy, Uncertainty, NGA's role?, Use to validate directly gathered data
- Multiple levels of uncertainty (data, model)
    - Move to knowledge, wisdom, insight
    - New paradigm of uncertainty (Based on analytical needs at hand)
- Advancement of Sensors
    - Sensor calibration
    - Smart sensors, miniaturization, on-board computing
    - Infrared, radar (better sensors)
    - Don't lose focus, Don't forget the sensors
    - Don't forget the core areas
    - Scenario modeling to deploy appropriate sensor for task (Weather, geography, etc.)
- Temporal Analytics
    - Partner with NSF, partner with other gov entities, and other international science entities

How do advances in the cross-cutting themes shape the 5 core areas?

- Can't lose track of the 5 core areas
    - cross-cutting themes support the cores, but can't ignore/replace the 5 cores
    - Cross cutting themes need to show value to the core areas, not a substitute
    - Mathematics, visual analytics can directly benefit NGA and its missions
- Adding Time to Space
    - Rich extension
    - How to do this? Visual analytics, 4D GIS, Time is difficult to represent, Temporal analytics?
- No stove-piping in 5 core areas
    - Also applies to cross-cutting areas
    - These areas blend together (look for and/or promote innovation at the intersection of these areas)
- Science development needs to be plugged into international science community