Overview of human-centric space situational awareness science and technology

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ABSTRACT

Several organizations within the government and industry are researching ways to help humans understand and react to events in space. Gaining space situational awareness (SSA) is both helped and complicated by the fact that there are numerous information sources that need to be planned (i.e., tasked), collected, processed, analyzed, and disseminated. This paper will outline areas of science and technology (S&T) related to human-centric SSA and space command and control (C2) and discuss related efforts within the Air Force Research Laboratory Human Effectiveness Directorate. A survey of other organizations working SSA human factors will be provided as will suggestions on where more attention may be needed. A large part of the research we are aware of is in support of the Joint Space Operational Center (JSpOC), National Air and Space Intelligence Center (NASIC), and similar organizations. Much recent research has been specifically targeting the JSpOC Mission System which has provided a unifying software architecture and vision.

Introduction

Situation awareness is critical to virtually all aspects of life. We need to be aware of the situation behind us when we back out of our driveway. We need to be aware of our children's whereabouts to ensure their safety. Awareness of our immediate surroundings can be challenging enough, but being aware of situations beyond our atmosphere can be orders of magnitude more difficult. Endsley [6] defines situation awareness as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." Brown [4] emphasizes that space situational awareness (SSA) requires integrating, fusing, analyzing and exploiting traditional and non-traditional space intelligence, surveillance, reconnaissance (ISR), environmental sensors, and system health and status information.

The Joint Space Operations Center (JSpOC) needs to maintain SSA to carry out their command and control (C2) mission [11]. The JSpOC Combat Operations Division maintains SSA in support of the Joint Functional Component Command for Space (JFCC-SPACE) who often needs to make critical decisions based on this [1]. Many SSA tasks involve monitoring, aggregating and reporting current status of various national space resources, as well as their relationship to other space objects and capabilities.

Command centers, including the JSpOC, have numerous tools at their disposal. But they are moving away from these stovepiped niche tools – each with their own "look and feel" – to architectures with a unified human-system interface or, as commonly referred to, a user defined operational picture (UDOP). In 2006-2007, the Air and Space Operations Center (AOC) had 88 different stand-alone tools. During a recent cognitive task analysis (CTA), the authors identified more than 75 different tools in use within the JSpOC [1]. Since this CTA, significant progress is being made with respect to the information architecture. A service-oriented architecture (SOA) has allowed stovepiped computer applications and databases to be integrated and share data.

Improved architectures and algorithms alone, however, do not necessarily make the decision maker's task easier. The data needs to be fused and presented in a way that allows humans to deal with the vast amounts of data and make sense of it. This requires correlating data in time and space, putting the right data together, dealing with conflicting data, and presenting results to the decision maker in a meaningful way [12].

Air Force Research Laboratory (AFRL), 711 Human Performance Wing, Human Effectiveness Directorate (711 HPW/RH or for this paper simply RH) have worked closely with space analysts and operators to address the unique human factor's needs inherent with SSA. RH has conducted CTAs and developed work-centered human-computer interfaces, visualizations, and collaboration technologies [2]. RH research aims to ensure that critical information coming from terrestrial and space-based sources are optimized for maximum exploitation by all end users.

RH's Battlespace Visualization Branch researches methods to exploit the visual channel primarily to improve decision making and operational effectiveness. The branch has a new, 5000 square foot reconfigurable laboratory where researchers investigate the latest visualization hardware, software, and techniques to facilitate situation awareness and decision making. The Visualization Laboratory is setup to emulate an operations center, particularly a space operations center, where many different display technologies can be evaluated for single users and groups.

In addition, this facility contains state-of-the-art display technologies that include nine 'true' three-dimensional displays including helmet-mounted displays, stereoscopic, auto-stereoscopic, volumetric and holographic. There are four types of multi-touch surface displays, including large display and table-top formats. The capabilities and state-of-the-art display technologies of the Visualization Laboratory provide the venue for conducting human-centric research for SSA technologies, as well as exploring new media for visualization in a controlled but operationally-representative laboratory environment. The laboratory also facilitates collaborative research with organizations such as AFRL Information Directorate (RI) with their Ergonomic Workstation (discussed later).

SSA human factors S&T areas

Human factors is a multi-faceted discipline. For SSA, this not only includes studying human-system interface but several other areas such as those depicted in Fig. 1 and described below.

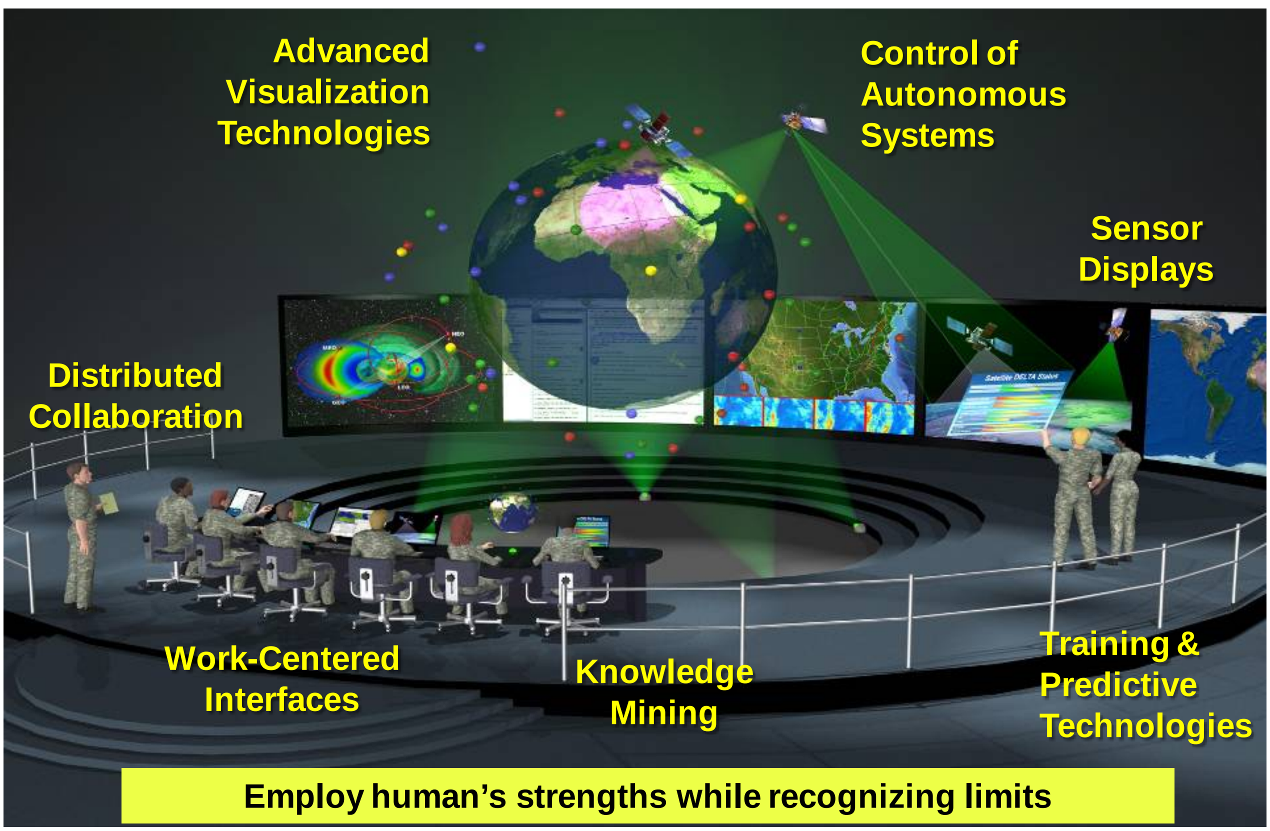

Fig. 1: SSA human-centric S&T areas.

Object and Data Visualization – Visualizations can provide an intuitive way to understand information, relationships, and meaning. More than just providing individual pieces of information, dynamic visualizations can convey geospatial and temporal relationships, and bring meaning to data from disparate sources. For example, operators and analysts need satellite catalog visualizations that convey the physical relationships between space objects. They may also need to make use of sensor data from multiple sources around the globe. Visualization research is needed to improve data trend analysis as in visual analytics and interactive visualization – e.g., satellite anomaly and space weather trends over time, and visualizations of computed reentry trajectories of large space objects (discussed later).

Workflow support – Today, people are overwhelmed with information tools. There are tools dedicated to highly specialized capabilities that are great – if only there was time to learn how to use them. Methods, therefore, are needed to orchestrate these tools to support work (decisions, analyses, concept formulation, etc.) in an optimal way. Human-computer interfaces need to be developed that encapsulate multiple computer services (i.e., algorithms, programs, or applications) into a unified workflow.

Training & predictive technologies – Modeling, simulation and employment of gaming technology are techniques used for both training and forecasting of cascading events. Although RH has had some related research in the past [7], we know of no ongoing research to advance SSA or space C2 training. Technologies are being developed for space event forecasting but, again, we know of little research into how humans can use them optimally.

Knowledge mining – Knowledge is power. But knowledge is of little use if it is not accessible to those who need it. Two approaches can be taken to provide knowledge and expertise: capture it in digital form (e.g., through expert systems) or provide links to the human experts. However it is not always practical to capture expertise in digital form. Experts often cannot convey how they know what they know or how they pick up on cues that others might miss. Therefore research performed on SBIR efforts, described in a following section, aimed to help locate human experts or link those with common interests (e.g., a specific space event).

Collaboration – Two heads are only better than one if they can communicate and collaborate effectively. As mentioned under knowledge mining, many people across the enterprise have wisdom to share or hold different pieces of the SSA puzzle. But once collaborators are linked, technology may be needed to facilitate their collaboration. We need to improve an individual's or team's ability to work with others in distributed locations through advanced video teleconferencing, shared virtual spaces, file sharing, virtual white-boards, chat, and knowledge search. Again, more research related to this are described below.

C2 – Developing and selecting courses of action (COAs) is central to virtually all military operations. The development and selection of space COAs includes tasking of satellites and sensors, defensive maneuvering of satellites, and control of microsatellites. Space C2 research is being performed by AFRL as discussed later.

Hardware/facilities – This area of research can include ergonomic workstations, immersive displays, interaction technologies, mobile computing and operations center layouts. The design of the operations center can have a dramatic impact on collaboration and overall operational effectiveness.

Advanced visualization technologies – To expand on hardware-related technology, some research is being conducted by RH and other organizations with true 3-D displays, touch displays, head-mounted and body worn displays, shared displays, and augmented reality displays to visualize relationships of objects in space as well as satellite position with respect to the user's position. With the rapid advancement of visualization technology, we are certainly in our infancy into the utility of these advanced visualization technologies for space operations.

RH research in SSA

RH has conducted research in SSA since 2002 [8]. During this time, several core funded, in-house, and Small Business Innovative Research (SBIR) efforts related to SSA have been initiated and are sampled below. As noted in each section, some of these efforts have been completed while others are ongoing.

STEED – RH's first SSA SBIR started in 2004 to investigate how new fusion technologies can be integrated into the workflow. The Satellite Threat Evaluation Environment for Defensive Counterspace (STEED) system (Fig. 2) [8], developed by The Design Knowledge Company (TDKC), employed RH's work-centered support system (WCSS) [5] concept that unified fusion algorithms from three AFRL Space Vehicles Directorate (RV) SBIR contractors [9]. The success of this RV/RH collaboration resulted in an AFRL rapid response effort (AFRL Core Process 3) to accelerate the transition. This eventually became a foundational technology for the JSpOC Mission System (JMS) [10].

Key elements of the Core Process 3 effort included initial prototypes of:

(1) Enhanced orbital catalog processing for all-on-all conjunction prediction and proximity awareness.
(2) A satellite database with pertinent satellite information, archiving, and net centricity.
(3) Multi-level distributed data fusion of satellite telemetry, space weather, and object catalog.
(4) Advanced visualization system for intuitive display and interface for information tailoring.

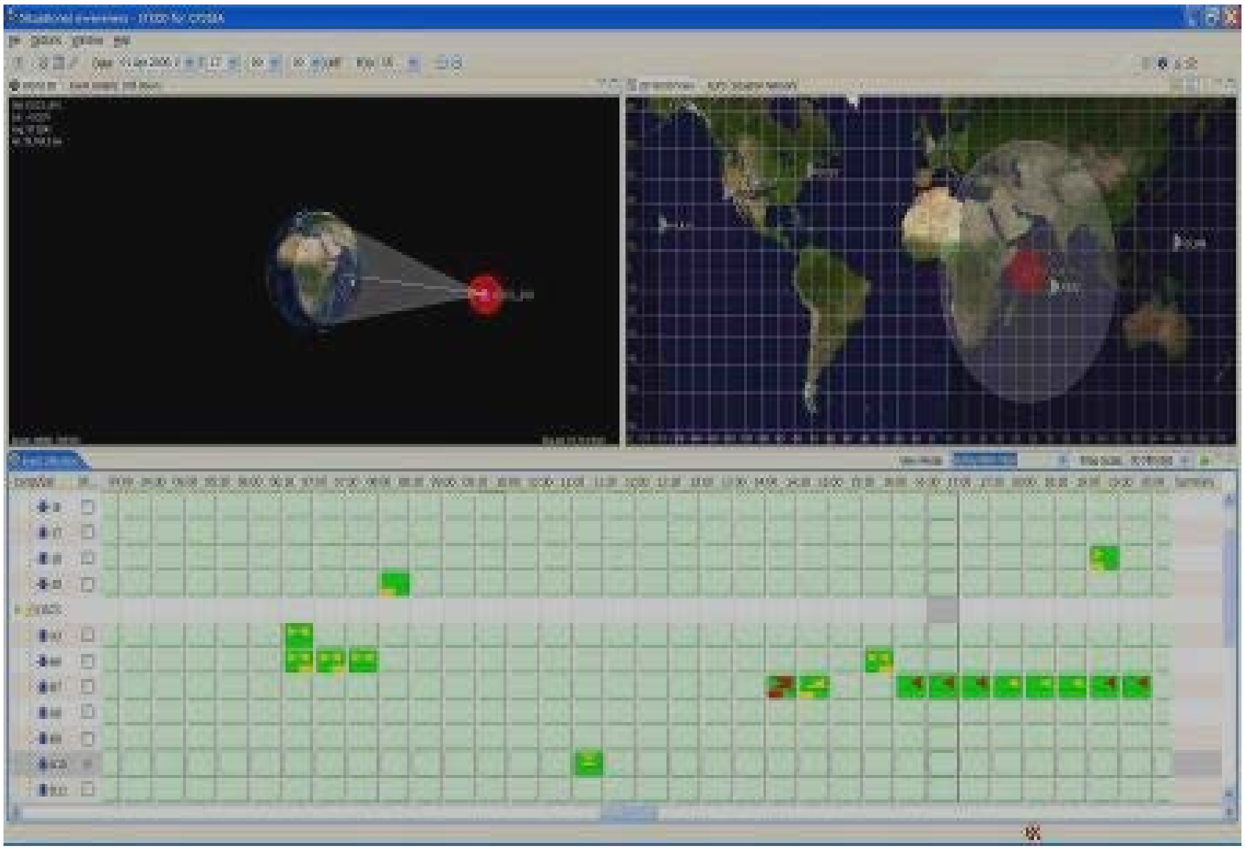

Fig. 2: Satellite Threat Evaluation Environment for Defensive Counterspace (STEED) circa 2005

Of course, this effort alone did not address all of the JSpOC needs and several key long-term research areas were identified. These included threat characterization and assessment, intelligence for SSA, data fusion performance metrics, dynamic sensor tasking, and optimal cognitive environments for operators.

<u>Cognitive Task Analyses</u> – Following the STEED effort it became clear that a more formal understanding of the evolving SSA enterprise was needed. RH thus conducted a CTA of the JSpOC and NASIC to lay the foundation for future SSA and space C2 work.

The ultimate goal of a CTA is to support the design of task-centered visualizations integrated into a work-centered human-system interface. The CTA process used in these studies considered people as information *actors* rather than as system *users*. The aim was to understand their work goals, how information was used and interpreted, and why they performed certain tasks. The methods and protocols developed for the CTA were based on Dr. James McCracken's dissertation and adapted for this domain [1].

The CTA of the JSpOC focused on the work done by various units that make up the JSpOC, the tools they currently use, the information they need, and how they collaborate with others as they prosecute their mission. It surveyed the structure of work for selected positions in particular jobs that involved extensive interaction with other entities such as the Satellite Operations Squadrons (SOPS), 50th Space Wing which operates the Air Force Satellite Control Network (AFSCN) sites, U.S. Strategic Command (STRATCOM), and NASIC. The CTA captured the structure of work, including cognitive, perceptual, temporal, strategic, environmental/contextual, and collaborative elements.

This CTA provided a direction for AFRL-developed JMS UDOP prototypes and related research. Understanding the type of flexibility needed to adapt the UDOP to evolving tools; Tactics, Techniques & Procedures; and doctrine was an important goal of this work. Providing guidance to the development of individual tools such as space environment visualization, collaboration, and decision support was another goal of the CTA. In order to accomplish this goal, we needed to understand in detail the tasks, and therefore, decision and information requirements of individual operators as well as their interaction and collaboration requirements. This work will not only provide a foundation for RH research but research of other directorates. The JSpOC has found the CTA report useful documentation for their operations.

Space Environment Visualization – Most space weather phenomenology cannot be seen, felt, heard, or smelled like we can with terrestrial weather. Given this and the limited audience for space weather analysis and the complexity of the space environment, visualizations of space weather have a long way to go to become nearly as intuitive as terrestrial weather displays. Visualizations are needed to convey the past, current, and future space weather situations with a focus on the potential impact to space assets.

Through SBIR efforts with TDKC and Aptima, new visualization technologies were developed to better understand the space environment. The workflow-integrated visualizations will better enable space components to assess overall conditions and determine impacts to space assets. After a series of successful demonstrations, Space Weather Information Fusion Technology (SWIFT), which was developed by TDKC, has gained advocacy by Air Force Space Command (A5). Fig. 3 is an example visualization that conveys space weather effects on satellites in various orbits.

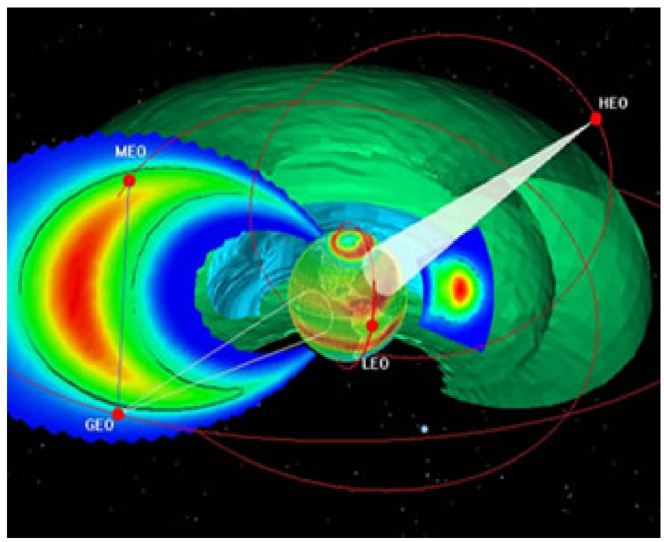

Fig. 3: Space Weather Visualization.

User Definable 4-D Common Operating Picture (COP) – The 4-D COP was an extension of the space UDOP work with a focus on providing air, space, and cyber information to the AOC analyst. In addition to providing insight into what is happening in all three warfighting domains, this SBIR effort links 3D visualizations with the time dimension, allowing operators to move backward in time to understand a developing situation or to move forward in time for planning and "what if" analyses. This TDKC effort was successfully demonstrated at Joint Expeditionary Force Experiment (JEFX) 2011 and ACE 2011.

Reentry Visualization – The JSpOC is the official source of reentry predictions for uncontrolled space objects [11]. Although the likelihood of impact near habitation is low, the JSpOC must determine possible impact times and locations in as far in advance as possible. They must also schedule sensors to observe the object's final orbits. The challenges inherent with this kind of trend analysis/reporting lie in how best to present highly technical information in readily-understandable ways for a fairly wide audience. This audience includes not only the engineers but also those less familiar with reentries such as senior leaders, diplomats, and top government officials.

RH in collaboration with AFRL Directed Energy Directorate (RD) and Naval Research Laboratory (NRL) performed a research effort to investigate optimal ways to visualize reentry information. The goal was to develop visualization concepts of the reentry paths and impact locations including likelihoods, as well as available sensor coverage for these paths.

TDKC was contracted to help RH develop visualization concepts and create an initial prototype. Fig. 4 depicts a visualization concept that was able to be implemented in software. This visualization made use of a Monte Carlo simulation developed by RD and NRL which represented the object's state vector trajectories for each of the simulation runs. An encapsulated geometry for the reentry state vectors (convex-hull, ellipse, and ellipsoid) was generated. Points on a 3D globe were displayed corresponding to each state vector location. The user could then click on any point to retrieve latitude, longitude, altitude, time, and run number. A time slider bar was also included to allow users to see the evolving cloud of predicted orbits over time.

The Monte Carlo state vectors were visualized on the 3D globe – again as illustrated in Fig. 4. NRL's data run is displayed in the 3D NASA World Wind view. The insert depicts a satellite ground sensor with dome.

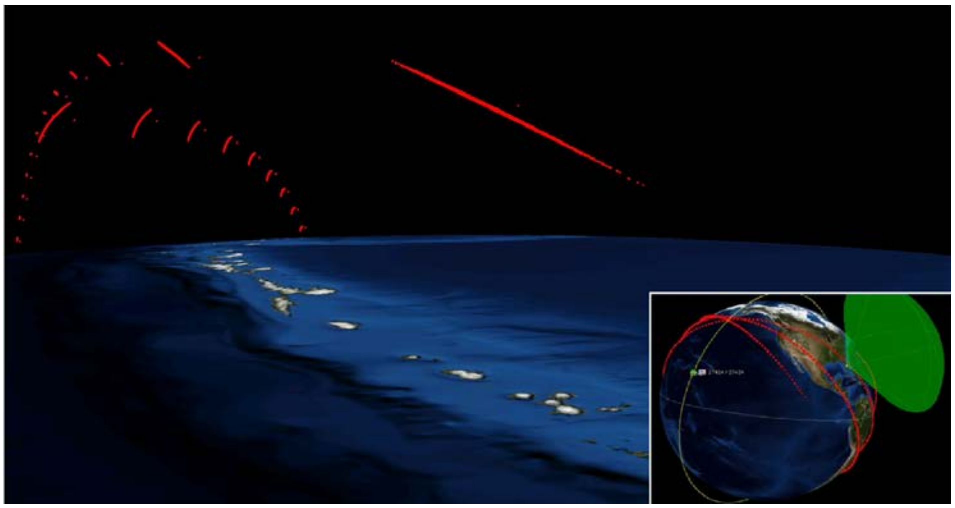

Fig. 4: Reentry data displayed on 3D NASA WorldWind view. Insert shows cone-shaped sensor coverage.

<u>Space Order of Battle Web Service</u> – In response to NASIC's desire to optimize packaging of space products for use by JSpOC operators, RH personnel transformed elements of NASIC's Space Order of Battle (SOB) to create a JMS web service. NASIC supported this activity with personnel time, accreditation, and vetting of the completed service. The transition was accomplished through collaboration with the JMS Program Office and AFRL/RV, who provided support by linking the SOB services to JMS Service Pack 3 released in December 2011 and currently in use on the JSpOC floor.

This web service allows JSpOC personnel to access data faster since it is delivered directly to the JMS desktop, rather than having to go to the NASIC website, and includes searching of the SOB tree or web services. Operators can auto-insert the desired data into briefing slides. This transition served as a model for how to deliver timely, net-centric intelligence from NASIC to the JSpOC, thus assuring timely transition of NASIC space products into JMS. Fig. 5 depicts the UDOP screen with SOB listing and 3D display of selected satellites with orbits and ground coverage.

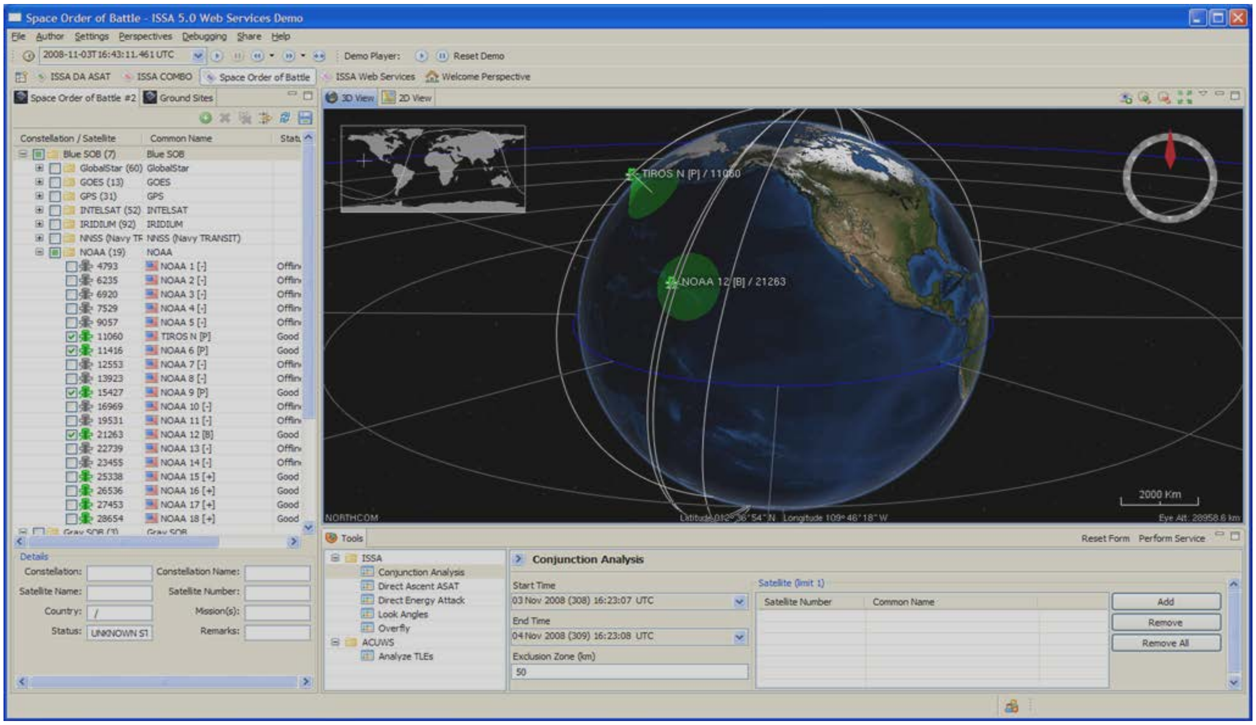

Fig. 5: Space Order of Battle Screen.

Ibex – RH is also developing visualization and human-system interface concepts on the Defense Advanced Research Projects Agency (DARPA) Ibex effort working particularly closely with NASIC.

Ibex demonstrates an advanced SSA data fusion based on Space Surveillance Telescope (SST) data and extendable to other current and future sensors—capability to dynamically task disparate sensors and efficiently process data to provide actionable information [3]. The objectives of the program are to develop and demonstrate algorithms and software to autonomously accept, organize, process and analyze SSA data in three primary areas:

- Dynamic Sensor Tasking (DST): synergistic and cooperative cueing for systems such as Space Based Space Surveillance (SBSS) and SST.
- Positive Object Identification (POI): reduce SSA data ambiguity through positive ID of space objects to maintain custody of all detectable objects.
- Rapid Object Characterization (ROC): supports quicker sensor response and object of interest (OOI) identification from uncorrelated targets.
- Provide more timely understanding of the space situation to support course of action implementation in the JSpOC.

SSA Visualization (SAVI) – An advanced technology development effort (6.3 research funding) was initiated in 2012 to prototype SSA human-system interface and visualization concepts. Based on a review of JSpOC needs, launch analysis was selected to be the first focus of this effort. At the time of this writing details were evolving on the effort but capabilities that may be supported include:

- Indications and warnings (I&W) preceding launch
- Country of origin
- Payload
- Trajectory including past and current positions of all stages
- Launch speed
- Projected path of all stages with confidence levels
- Locations of possible Earth impact with confidence levels
- Possible security risks
- Sensor coverage

This RHCV effort is to conclude with a demonstration in late 2013. Knowledge elicitation of potential users and launch service providers has started.

Other organizations performing SSA human factors research

We have covered much of RH's work above, but other organizations are conducting SSA human factors research. Although not necessarily sponsored or endorsed by the JMS Program Office, much of the research discussed here are targeted at the JMS UDOP and intended to align with the JMS vision. Although no detailed master plan exists for SSA human factors, we believe all are targeting important areas and see little redundancy.

AFRL Information Directorate's (RI's) ErgoStation (Fig. 6) provides a customizable, mobile, and cost-effective 3-screen workstation that can be used either sitting or standing. In addition, RI has performed research in space command and control (Advanced Space C2 Execution Management program) and air, space, and cyber UDOP that leverages their JView tool. JView is a 3D runtime configurable and platform independent application programming interface (API) upon which robust visualization tools can be built [13].

Fig. 6: RI-developed ErgoStation.

A number of contractors have made significant contributions to SSA and space C2 human factors. Neither the authors nor the government endorse any of these companies and consider this just a sample of commercial efforts that support JSpOC human factors. Most of these companies have worked with the authors of this paper but many other organizations have certainly made and continue to make important contributions to the area.

The Massachusetts Institute of Technology (MIT) Lincoln Laboratory is a major player, along with AFRL, in the DARPA Ibex program. Although they have not been focusing on JMS human factors specifically, they have developed UDOP screens for their algorithms and applications. Certainly their deep understanding of SSA technologies helps in bridging the gap between the sensor and the decision maker.

Analytics Graphics, Inc. (AGI), the developers of Satellite Tool Kit (STK), has provided demonstrations of innovative SSA visualization concepts that take advantage of the power of their simulations and analysis capabilities. AGI has also worked collaboratively with 711 HPW/RHCV to provide feature enhancements to its original Satellite Augmented Reality (AR) application in support of SSA risk reduction activities (Fig. 7).

Fig. 7: AGI's Satellite AR app for Android devices.

Applied Minds, Inc. created a future vision of how to achieve optimal SSA through the “JSpOC of the Future” demonstration (JSpOC 3.0, Fig. 8), developed at their facility in Glendale, CA. Their efforts resulted in the design and build of a full-scale, multi-faceted command center mockup that demonstrated advanced tools and techniques for distributed collaboration, data fusion, visualization, and adaptive planning. Applied Minds paid special attention to engineering for human factors, focusing on human-machine interfaces, ergonomic workstations, immersive displays, tools for enhanced situational awareness, and a design intended to increase stamina to optimize operations. The entire effort, carried out using rapid prototyping and story-based design and development methods, presented the vision in a compelling, interactive, experiential scenario-based demonstration.

Fig. 8: Applied Minds’ JSpOC of the Future demonstration.

In addition to their original work-centered SSA research mentioned above [9] and other SBIR projects managed by RH, TDKC is under contract to RV to develop the current JMS UDOP releases and to perform advanced technology developments. TDKC has developed space weather visualizations, reentry visualizations, and methods to mine for specific SSA expertise that is not in digital media. TDKC also has roles in RH's DARPA Ibex and NRO efforts as well as an advanced technology development for launch analysis.

Summary

The human factors research described in this paper is a good start but we still have much to do. Despite success in automating some processes, SSA and space C2 are still highly dependent on human analysis, judgment, dissemination, collaboration, and decision making. With the vastness of the physical domain, the complexity of the operations, the plethora of highly technical data, and the criticality of space to national defense, we must develop the most effective tools and facilities we possibly can. We must also maintain the most highly trained and qualified space professionals in the world. Human-centric research should move us in the right direction.

References

1. Aleva, D. and McCracken, J., *JSpOC Cognitive Task Analysis*. Advanced Maui Optical and Space Surveillance (AMOS) Conference Proceedings, 2009.
2. Aleva, D., Ianni, J. D., and Schmidt, V., *Space Situation Awareness Human Effectiveness Research Trends*, World Congress in Computer Science, Computer Engineering and Applied Computing Proceedings, 2012.
3. Blake, T., *Space Domain Awareness*, AMOS Conference Proceedings, 2011.
4. Brown, P. A., *Promoting the Safe and Responsible Use of Space: Toward a 21st Century Transparency Framework*, HQ AFSPC, High Frontier 5, no. 1, 2008.
5. Eggleston, R. G., Roth, E., Whitaker, R., and Scott, R., *Conveying work-centered design specifications to the software designer: A retrospective case analysis*, Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting. (pp.332-336). Santa Monica, CA: Human Factors and Ergonomics Society, 2005.
6. Endsley, M. R., *Toward a Theory of Situation Awareness in Dynamic Systems*, Human Factors 37(1) 32-64, 1995.
7. Guilfoos, S., *Standard Space Trainer (SST) Offers Expanded Simulation Features*, Air Force SBIR/STTR Transition Story, 2008.
8. Ianni, J., *Work-Centered Support for Counterspace Operations*, American Institute of Aeronautics and Astronautics (AIAA) Space 2004 Conference and Exposition Proceedings, 2004.
9. Ianni, J. and Zetocha, P., *Data Fusion for Space Situational Awareness*, AFRL Technical Horizons Magazine, December, 2006.
10. Morton, M. and Roberts, T., *Joint Space Operations Center (JSpOC) Mission System (JMS)*, AMOS Conference Proceedings, Maui, HI, 2011.
11. Rendleman, J., *Joint Space Operations Center & SSA Sharing*, presentation for the AIAA Space Operations & Support Technical Committee Workshop, 2012.
12. Roth, E. M., Patterson, E. S. and Mumaw, R. J., *Cognitive Engineering: Issues in User-Centered System Design.* In J. J. Marciniak (Ed.), Encyclopedia of Software Engineering, 2nd Edition. New York: Wiley-Interscience, John Wiley & Sons, 2002.
13. Sarnacki, A., *AFRL Releases Audit Trail Viewer (ATV)*, SURVIAC Bulletin, Volume XIX Issue 1, pp. 1, 2003.