End-to-End Design and Objective Evaluation of Sensor Web Modeling and Data Assimilation System Architectures: Phase II

Stephen J. Talabac and Michael S. Seablom
NASA Goddard Space Flight Center
8800 Greenbelt Road
Greenbelt, MD, 20771

G. David Emmitt and Sid Wood
Simpson Weather Associates, Inc.
809 East Jefferson Street
Charlottesville, VA 22902

Robert Atlas
NOAA Atlantic Oceanographic and Meteorological Laboratory
4301 Rickenbacker Causeway
Miami, FL, 33149

Joseph Ardizzone
Science Applications International Corporation
4600 Powder Mill Road, Suite 400
Beltsville, MD, 20705

Robert Burns and Eric Kemp
Northrop Grumman Information Systems
3975 Virginia Mallory Drive
Chantilly, VA, 20151

Abstract. **We present results from our on-going effort to construct a "Sensor Web Simulator" (SWS) for use in Earth Science mission planning. The goal is to demonstrate how advanced information technology can reduce mission costs, extend mission life, and enable better data collection through the collaboration of observing system assets and numerical models. The simulator, as designed, will be a fully integrated information system enabling technologies for Earth observing systems and related data information systems to be thoroughly evaluated for current and future missions. Our work is focused on three potential Decadal Survey missions: the "3D Winds" mission; the Extended Ocean Vector Winds Mission (XOVWM); and the Precipitation and All-weather Temperature and Humidity (PATH) mission. The Geostationary Operational Environmental Satellite R-series (GOES-R) mission will also be included in our research as it complements and augments the measurement characteristics of the three Decadal Survey missions. We will discuss the development of the simulator to date, preliminary results that were obtained from our Phase-I effort, and a hurricane use case scenario in our Phase-II work. We will also discuss the utility of the simulator for performing "What if?" scenarios for mission trade studies.**

I. Background

Although initial steps have been taken to foster integrated observing systems, current remote sensing observing systems are dominated by operations concepts that rely on measurements from independently operated missions and science instruments. Information fusion by the ground segment is commonplace *after* the mission data has been collected, downlinked, and processed. However, information sharing among remote sensing platforms is not an intrinsic part of the observation planning process or the subsequent execution of instrument measurement sequences. Current space and ground segment architectures and mission operations concepts support global, synoptic measurements, but they do not readily facilitate autonomous, collaborative data collection techniques or adaptive observing strategies. With few exceptions, spacecraft and instruments lack the ability to respond to rapidly evolving, transient, or variable conditions by reconfiguring their spatial, temporal, spectral, and other measurement modes. Instead, most spacecraft operate in a single global data collection "survey" mode where the instrument is simply "on". Atmospheric systems that are in the very early stages of formation may not be observed, resulting in the loss of critical information that could lead to a better, more comprehensive understanding of how features come into existence and evolve. Those platforms and instruments that are able to change their observation strategy or measurement modes typically rely upon manually intensive processes and procedures that may not provide sufficient lead time to reconfigure and redirect sensors to make the required measurements.

Data assimilation systems and numerical weather prediction models rely upon thousands of remotely sensed and *in situ* measurements that are collected nearly continuously. Invariably, model error growth tends to increase as the forecast atmospheric state is projected farther out. Methods are available that can identify regions where models may be especially sensitive to initial conditions. Algorithms may also be used to detect potentially significant atmospheric signatures present in the model forecast. *Model-derived information can thus be potentially very useful in deciding where, when, and how to direct our remote sensing assets to make "intelligent" targeted measurements.* The notion of implementing a reinforcing feedback loop between forecast model output and on-orbit asset data collection, such that measurement modes are dynamically modified to yield an overall benefit to observing system behavior, offers the potential to: (i) improve efficient utilization of our space assets, and (ii) quantifiably improve predictive skill by collecting and assimilating measurements that are of most value to numerical prediction weather models. *Observing systems that take advantage of these reinforcing feedback loops by dynamically reconfiguring their measurement modes in response to model-derived information are called Model-driven Sensor Webs. They are the focus of our research.*

II. Sensor Web Simulator Rationale

Investing in the design, implementation, and deployment of such a large, complex sensor web observing system would be very costly and almost certainly involve significant risk. To optimize the process, we are building a Sensor Web Simulator (SWS) to facilitate detailed studies of proposed sensor web observing systems *before* large investments are made to develop, deploy, and operate these complex systems. When the SWS is completed, users will be better able to investigate "What If?" scenarios of different sensor web configurations and operations concepts, and objectively evaluate how predictive skill is affected by particular combinations of assets, instruments, and measurement strategies. After converging on a viable architecture and an operations concept, detailed analyses can then be performed by mission and instrument engineering design teams to develop and recommend a solution satisfying mission parameters and constraints.

The SWS leverages the integration of off-the-shell simulation and analysis software with custom developed applications, as well as extensive experience by our team members in the design, execution, and objective evaluation of Observing System Simulation Experiments (OSSEs).

A. OSSEs

A key attribute of the SWS is the ability to perform OSSEs. They provide the framework for testing sensor web concepts. An *OSSE* is an experiment designed to assess the potential impact of planned missions or changes to existing missions on numerical weather prediction. It enables the benefits of an observing system to be estimated before it is designed, built, deployed on-orbit, and put into operational use. Trade-offs in instrument design characteristics and measurement modes, spacecraft orbital configurations, and methods of assimilating data that is expected to be produced by the observing system can be performed thus yielding potentially significant reductions in development time and cost. [2]

B. The Nature Run

In order to conduct an OSSE, a simulated atmosphere must first be created that is representative of what we see in reality. This simulated atmosphere is called the *Nature Run (NR)*. The NR is created by integrating a weather forecast model over long periods ranging from weeks to months in length. Memory of the initial "real" atmospheric state diminishes over time yielding a "simulated" atmosphere. This new atmosphere must mimic reality for the spatial and temporal scales required for simulating various observing systems. The process of making that determination is known as validation.

Once validated, the NR becomes the source for simulating observations and the truth for measuring the impact of assimilating those observations. Simulated observations must include inherent errors associated with the instrument, retrieval process, and various atmospheric conditions. In addition, the impact of assimilating a control set of observations (i.e. observations in use operationally) must yield the impact that we see in reality. The process of tuning the various error characteristics to yield a realistic impact is known as calibration.

C. An OSSE System

A validated NR along with the calibrated observations is collectively known as an *OSSE System*. It includes the model and data assimilation system (DAS) used in the calibration. Collectively, these components become the framework for simulating additional observations and executing the OSSE. *The SWS is being designed to work with multiple OSSE systems using an architecture that promotes modular service oriented protocols as the adaptable mechanism.* In this manner, established OSSE systems can be harnessed with minimal investment. See Ref. [2] for a complete description of OSSE methodology and examples of earlier OSSE results.

III. Phase-I Project Summary

In Phase I of our research we: (i) developed a software architecture for the SWS; (ii) designed and implemented an initial core suite of software sufficient for us to perform preliminary "proof-of-concept" testing; and (iii) designed and tested preliminary use case scenarios for a single spacecraft mission - the Global Wind Observing Sounder (GWOS). This mission is now referred to as the "3D Winds Mission" in the Decadal Survey. It is important to note that at the completion of our Phase I research, only a limited number of the software components that comprise our architecture were fully developed and integrated. Our initial GWOS use case tests thus required manual sequencing of the work flow needed to perform end-to-end testing. As we will discuss in Section IV, key components of the SWS have subsequently been enhanced in capability and more fully integrated as part of our Phase II work. This facilitates greater degree of automation as we continue to design and execute more sophisticated end-to-end use case scenarios.

A. System Architecture

The SWS is a sophisticated simulation environment that simulates the operation of a dynamic, model-driven sensor web system. It is in essence an analysis tool that integrates the capabilities needed to create and execute sensor web scenarios, to render results in 2D and 3D visualizations, and eventually to statistically analyze the simulation results. The software framework is a layered architecture that provides all of the tool functionality (Fig. 1). It includes layers for the user interface, scenario execution, and science and engineering models.

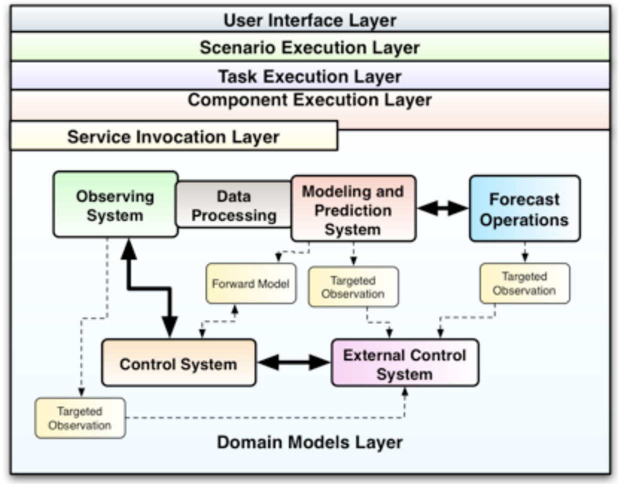

Fig. 1 - Sensor Web Simulator Architecture

The current SWS architecture relies on the use of a workflow tool (WFT) that: (1) provides a simple, but useful user configuration for scenario settings; (2) performs complex simulations; and (3) monitors the simulation activities as they execute. With it we can create the use case simulations that we have executed thus far. However, the development effort can be significant with certain new use case scenarios that we are beginning to conceptualize. The reason is that the WFT is not a true simulation engine. The latter is better suited to handling dynamic events. Although the WFT implementation for the current SWS provides a level of extensibility to accommodate use cases having characteristics similar to those use cases that we have explored to date, its extensibility is limited for other more complex use case scenarios. This is one aspect of the architecture we will examine for potential modification in Phase-II (Section IV).

The SWS currently uses a NASA OSSE system based on the Finite Volume General Circulation Model (fvGCM) NR at 0.5 degree resolution. It includes the NASA Goddard Earth Observing System Data Assimilation System (GEOS-DAS) [1] for the Modeling and Prediction System component. The GEOS-DAS includes: (1) a complex quality control system similar to that used operationally by the National Weather Service; (2) the Gridpoint Statistical Interpolation (GSI) program, which performs 3-D variational data assimilation; and (3) the GEOS-5 atmospheric general circulation model.

B. Wind Lidar Use Case

To help guide the design of the SWS, we set up and executed a "zeroth-order" simulation in Phase-I that tested the use of model-directed observations. The experiment used synthetic observations based upon the proposed GWOS mission - aka the Decadal Survey Plan "3D Winds Mission" [3]. Most of the major elements of the simulator were engaged and the software components were run manually and sequentially.

GWOS (launch ~2020) is a Doppler Wind Lidar (DWL) mission comprised of a hybrid sampling technology that takes advantage of direct detection and coherent detection sampling methods. Mission objectives are to improve understanding and prediction of: (i) atmospheric dynamics and global atmospheric transport, and (ii) global cycling of energy, water, aerosols, and chemicals. The objectives will be achieved using space based lidar measurements that yield vertical profiles of the horizontal wind field to provide a complete global 3-D picture of the dynamical atmospheric state. A benefit of assimilating the 3-D wind field will be a more accurate representation of the initial conditions for numerical weather models.

To obtain complete vector wind components, GWOS must sample an air parcel from at least two different perspectives. The proposed instrument is comprised of coherent and direct detection lidars that operate through four telescopes. Two telescopes are oriented nominally ±45° in both azimuth and elevation pointing in front of the spacecraft, with the other two similarly oriented pointing aft. The combination of fore and aft line-of-sight laser shots produce an estimated vector wind for multiple vertical levels. During its 2 year mission lifetime, the coherent detection subsystem will take approximately 300 million shots, and the direct detection laser subsystem will take approximately 6 billion shots, with pulse repetition frequencies (PRF) of 5 Hz and 100 Hz for the coherent and direct detection laser subsystems respectively.

Using sensor web concepts, we investigated a modification to the GWOS operations that would (i) minimize the required number of lidar shots without compromising information of the atmospheric state, and (ii) target data collection for specific regions of the atmosphere that would potentially have the greatest impact on forecast skill. For (i) GWOS was provided the first guess wind field from a global forecast model (discussed below). Observed line-of-sight winds from the GWOS fore shot were compared with the predicted winds from the model and valid at the time of the observation. If the winds were considered to be in adequate agreement, the aft shot was not performed. If such agreement were ubiquitous there could be a substantial reduction in the lidar duty cycle, thus potentially extending the life of the instrument. For (ii) we used estimates of the model forecast error to direct GWOS to target those regions of the atmosphere estimated to be in a state of low predictability, and/or target sensible weather features of interest. To capture the maximum number of targets required slewing of the spacecraft (i.e., a roll attitude maneuver).

C. Use Case Test Results

Through our partnership with Simpson Weather Associates, Inc., we acquired a sufficiently large sample of simulated lidar data. This comprised an approximate 50-day sample of u- and v-wind components from a simulated conical-scanning lidar, and was properly sub-sampled to simulate the look angles that would be available from GWOS. For data assimilation with GSI, the lidar observation errors were defined as identical to those for rawinsondes. For (i) we set up a control case which used no lidar data, a case in which lidar data were used only where there was "significant" disagreement with the forecast winds, and a case in which all lidar data were used. Because the SWS version of the GSI did not support assimilation of line-of-sight winds, our experiment made use of only full vector wind components. This would be undesirable for operations but was deemed acceptable for the purpose of (i), i.e., design of the overall architecture. The model first-guess zonal wind components were therefore compared to the simulated lidar zonal wind components as a proxy for a line-of-sight comparison. Lidar wind profiles in close agreement with the model first guess were withheld, in essence "turning off" the aft shot for those profiles. Changing the criteria for this determination would allow mission designers to weigh the benefit of reducing the lidar duty cycle against the overall impact to the science (i.e., predictive skill or another quantifiable metric).

A 20-day period was selected for executing the configurations. Five-day GEOS-5 forecasts were launched from each of the 0000 UTC assimilation periods. For this sample period, nearly 80% of the lidar wind profiles compared favorably with the model first guess and were withheld from the data assimilation cycle. In operations, this would translate to a duty cycle reduction of about 30% (the minimum duty cycle would be 50% with the fore shots taken continuously). To test whether the duty cycle reduction had any negative impact on the forecast skill, we employed the commonly-applied anomaly correlation.

Not surprisingly, the full lidar set had the highest correlation while the control set (no lidar data) had the worst. The simulation of a reduced lidar duty cycle (i.e. targeted observations only) was similar to the full lidar results in the Northern Hemisphere. Results for the Southern Hemisphere were more difficult to interpret.

For (ii) we conducted a set of experiments to examine the impact of slewing GWOS for adaptive targeting. This included identifying so-called "sensitive regions" in the atmosphere (regions where the forecast is highly responsive to analysis errors) and autonomous detection of features of interest (e.g., tropical cyclones and jet streaks). Adjoint techniques [4] have proven to be successful in the determination of sensitive regions of the atmosphere. Our work plan includes the eventual incorporation of the adjoint technique under development by the NASA Global Modeling and Assimilation Office [5]. Acknowledging the project time constraints for the test case, we employed a less sophisticated method that calculated the difference between a 12-hour and 36-hour forecast of 500-hPa heights valid at the same time. If the atmosphere was in a perfectly predictable state, the difference between the two forecasts should be zero. Large differences between the two forecasts would be used to make targeted observations with the lidar by slewing the spacecraft for the purpose of capturing as many of the sensitive regions as possible.

We also included a set of rule-based targets to demonstrate the functionality of the External Control component of the SWS. The targets were prioritized in the order of the following subcategories:

1. Feature is over land
2. Feature is over the coastline
3. Feature is over ocean but is approaching land
4. Feature is over ocean and is moving away from land
5. Feature is over ocean and is far from land (> 1000km)

To emulate the effects of slewing we generated additional synthetic lidar data that were positioned ±150 km off the nadir-viewing angle of the instrument. For this experiment, approximately 33% additional data were captured over the targeted features.

IV. Phase-II Project Summary

A. Expanding the Simulator

While a number of functional components for the SWS were completed in Phase-I, areas are being identified for further abstraction and flexibility. For example, the ability to run multiple instances of the same satellite (e.g., two GWOS satellites in different orbits), the addition of new types of sensors, or the addition of new spacecraft, were not supported in the Phase-I version of the SWS. As Phase-II development began, we implemented some of these abstractions making it easier to plug in new components. Sophisticated scenarios still require careful orchestration of simulated elements since there is a specific order in sequencing events using the WFT (e.g., execute a spacecraft orbit model before gathering the required simulated observations).

As work on future use cases proceeds during Phase-II, we will modify the architecture to accommodate the creation of more complex and dynamic scenarios. Currently we can add new components and capabilities by extending a smaller wrapper code and adding configurable properties to the workflow. Ultimately, for maximum flexibility, a dynamically generated scenario definition will be needed to allow components to be reconfigured for existing and future scenarios. The management portions of the SWS can then use the scenario definition to direct the scenario execution.

B. Decadal Survey Missions

We have identified three Decadal Survey missions to drive the development of meteorological use case scenarios in Phase-II. As in Phase I we will continue to use GWOS [3]. We will add the Extended Ocean Vector Winds Mission (XOVWM) [6] and the Precipitation and All-weather Temperature and Humidity (PATH) mission [7]. We also plan to use the Geostationary Operational Environment Satellite R-series (GOES-R) [8] [18] meteorological satellite(s) as we formulate new scenarios.

XOVWM (launch ~2013-1016) is a proposed QuikSCAT follow-on mission. Equipped with a dual-frequency scatterometer, the XOVWM primary objective is to make all-weather, high horizontal spatial resolution measurements to determine the speed and direction of global ocean surface vector winds "to enable significantly improved severe storm and coastal hazard forecasts." [6] Of particular significance for our project, we plan to use a suitable proxy mission for XOVWM to provide data that will contribute to hurricane and extra-tropical cyclone detection and evolution, and wind field characterization. Hurricane and tropical cyclone detection will drive our initial science use case.

The PATH mission (launch ~2016-2020) is proposed as a geosynchronous spacecraft equipped with a microwave radiometer (i.e., sounder) that will make all-weather measurements of atmospheric humidity, temperature, and precipitation every 15 - 30 minutes. The sounder is planned to operate in the same temperature and water vapor bands used by the Advanced Microwave Sounding Unit (AMSU) instrument [9]. The primary purpose of the PATH mission will be to observe hurricanes and severe storms. Recent advances in technology offers the possibility to fly microwave sounders on geosynchronous platforms which can provide hemispherical coverage of the earth at much higher temporal rates than current and planned NOAA polar orbiting meteorological spacecraft.

The GOES-R mission is the first of a new series of NOAA geosynchronous meteorological spacecraft. Launch is planned in ~2015. Its orbit will provide continuous, real time atmospheric monitoring of the eastern and western US hemispheres. Of particular interest to our project is the Advanced Baseline Imager

(ABI), the spacecraft's primary instrument. The ABI will provide imaging capability in 16 channels at spatial resolutions of 0.5 km for the visible bands, 1 km for the near-IR bands, and 2 km for the IR bands. The ABI will image the entire full earth disc in 5 minutes and perform CONUS imaging every 5 minutes. It will also provide a rapid scan imaging capability (Mesoscale Imaging Mode) permitting a 1000 x 1000 km region of interest to be scanned in 30 seconds. The GOES-R mission provides us with the opportunity to explore potentially beneficial sensor web ops concepts for invoking the various GOES-R measurement modes by using information derived from one (or more) of the three Decadal Survey missions and information that can be derived from numerical weather prediction models.

C. *Tropical Cyclone Use Case Scenario*

As previously described, in Phase-I we demonstrated the potential impact of a model-driven use case for GWOS. A breadboard system was constructed to demonstrate the various components. In Phase-II we plan to execute a sensor web scenario using multiple spacecraft managed under a fully functional simulator.

Three Decadal Survey missions are used in this scenario: XOVWM, GWOS, and GOES-R. 10-m winds derived from XOVWM will be analyzed using a vorticity algorithm tuned to locate tropical cyclogenesis in the Atlantic basin (largely following [10]). These areas become high priority targets for observation. A list of these and other targets will be sent to the scheduler for GWOS and GOES-R. The scheduler uses an optimization scheme to determine the maneuvers necessary to acquire the specified targets. For GWOS, this may require slew maneuvers to the left or right of its nominal "nadir" ground track. Issues such as roll angle and proximity to the center of the targets are considered during the optimization. GOES-R is scheduled to go into a Mesoscale Imaging mode over one or more regions that encapsulate the targets.

D. *Generating Synthetic Observations*

Three external simulation models are used to create the synthetic observations for XOVWM, GWOS and GOES-R. This is consistent with the service-oriented architecture of the simulator.

The Doppler Lidar Simulation Model (DLSM) [11] is used to simulate 3-D wind profiles from GWOS. This includes line-of-sight winds derived from both forward and aft lasers and the composite full-vector wind simulation using Direct and Coherent detection systems. All effects of roll angle on the retrieval of these winds are simulated in addition to atmospheric effects.

A new Scatterometer Simulation Model (ScatSM) produces simulated ocean wind speeds and directions at 10 meters. Currently supported scatterometers are QuikSCAT (25-km resolution) [12] - Ku band and ASCAT (50-km resolution) [13] - C band. Wind speed and direction errors due to low/high wind speeds and precipitation [14-15] are included. Land and precipitation quality data flags are also included. The combination of C-band and K-band simulation capabilities will be used to approximate the dual frequency capability of an XOVWM instrument.

The new Cloud Motion Wind Simulator (CMWS) [16] [17] is used to simulate cloud motion winds from GOES-R. The model has been tuned to reflect the current distributions and densities derived from operational geosynchronous satellites as well as the expected densities and distributions of the future GOES-R (both nominal and rapid scan scenarios). A sub-algorithm has also been developed for simulating the well-known slow bias in retrieved cloud track winds.

E. *Using the Simulator for Decision Support*

The SWS will enable scientists to execute the above-mentioned scenario in various incarnations inspired by "What If?" questions such as: What if there were two GWOS satellites? What if there were two XOVWM satellites? What if the GWOS platforms were not maneuverable (i.e. slew maneuvers are not supported)? What is the impact of XOVWM, GWOS and GOES-R separately and in combination? What if GWOS used only direct detection technology? What if GWOS used coherent detection only? What if other targeting methods were used? These and other questions can be configured using the simulator to assess trade-offs in instrument design, orbit configurations and targeting strategies.

The SWS currently has the capability to support a finite number of variations on implemented use cases. A user invokes the graphical user interface (GUI) for the SWS and is presented with a configurable set of parameters (Fig. 2).

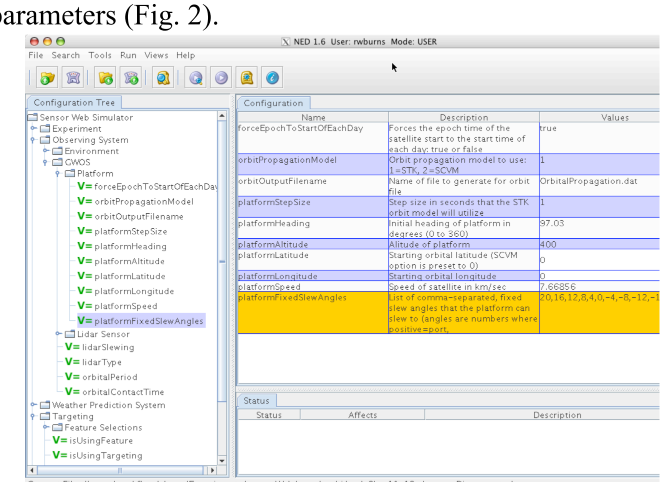

Fig. 2 - Sensor Web Simulator User Interface

The GUI provides a large number of settings and variables that can be modified for each scenario. Each of these settings controls various aspects of the models, algorithms and system settings for the components of the tool. They are identified in advance and exposed in the GUI for the user to change.

Once the user has settled on a specific configuration, he or she can launch a simulation using those settings and monitor and control its progress. Simulations frequently require a long wall-clock time to execute, thus making this feature particularly helpful.

The SWS also supports interactive tools, allowing the user to adjust certain aspects of the simulation as it runs. For example, an interactive targeting tool allows users to modify the default set of observation targets identified by the targeting algorithm.

To answer the "What If?" questions, a series of metrics can be calculated to assess the results of the various scenarios. Metrics include anomaly correlations to assess global impacts on forecast skill, and cyclone track and intensity errors. Because these metrics are often executed on an ensemble of forecasts, the user interface for the SWS will be expanded to allow metric calculations upon completion of all simulation runs. This may include a visualization package for displaying analysis, forecast and targeting results along with the simulated observations and the NR for verification.

V. Summary

The SWS is a comprehensive system for evaluating future missions that takes advantage of model-driven sensor web observation strategies and dynamic measurement techniques. Its service-oriented design provides flexibility and expandability as new technology becomes available for mission planning and design.

The OSSE system is at the core of all simulation studies. The simulator must be able to adapt to increasingly more sophisticated trade studies requiring higher fidelity in both resolution and scope. For example, pattern recognition algorithms exist for detecting severe weather outbreaks by examining features in clouds. A potential use-case scenario might involve targeting severe weather outbreaks by applying these algorithms to GOES-R visible or IR imagery. However, the OSSE system must be based on a NR capable of producing this level of realism in the simulated cloud fields.

The principal OSSE system in use to date is based on the NASA fvGCM 0.5 degree NR. All components related to the simulation of observations and the model/data assimilation system used to perform Numerical Weather Prediction (NWP) experiments are inherited by the simulator when using this OSSE system. Other OSSE systems are currently being considered. NASA and NOAA are creating OSSE systems based on the ECMWF T511 NR. It is a higher resolution NR created using the ECMWF model forecast system. ESRL and other organizations are developing mesoscale OSSE systems that will enable phenomena such as hurricanes and thunderstorms and the associated observations to be simulated at the resolution needed to meaningfully resolve these features.

Future work will be required to make these OSSE systems available to the simulator. Each OSSE system replaces the functionality in several layers of the simulator ranging from the simulation of observations to the data assimilation system used for NWP experiments. The service-oriented design provides a mechanism for doing this. However, in the absence of a general ontology for describing an OSSE system, new services must be built that can be inherited by the SWS at the time of execution.

In June we plan to complete our initial set of modifications to the SWS software. This will enable us to begin testing our first hurricane use case scenario under Phase II. We plan to run a control experiment followed by several other experiments involving the control and simulated data from one or more missions (e.g., XOVWM, GWOS, GOES-R). These initial experiments are planned to be completed in August at which time we can then begin to evaluate results by calculating statistics (e.g., track and intensity errors) for each forecast run.

VI. Acknowledgments

We wish to acknowledge ESTO for providing the funding for our current Phase II research and development project. We also wish to recognize Mr. Joseph Terry and Ms. Genia Brin who had contributed to the success of our ESTO AIST-funded Phase I Sensor Web Simulator prototyping R&D project.

VII. References

[1] M. M. Rienecker et al., "The GEOS-5 Data Assimilation System — Documentation of versions 5.0.1, 5.1.0, and 5.2.0," Technical Report Series on Global Modeling and Data Assimilation, vol. 27, 2008. http://gmao.gsfc.nasa.gov/pubs/docs/Rienecker369.pdf.

[2] R. Atlas, "Atmospheric observations and experiments to assess their usefulness in data assimilation," J. Meteor. Soc. Japan, vol. 75, pp. 111-130, 1997.

[3] R. Kakar et al., "Overview of an advanced earth science mission concept study for a global wind observing sounder," unpublished. [Presented at Working

Group on Space-Based Lidar Winds Meeting, 6-9 Feb 2007, Miami, Florida; slides available on-line at http://space.hsv.usra.edu/LWG/Feb07/Papers.feb07 Kakar.feb07.ppt]

[4] M. Leutbecher and A. Doerenbecher, "Towards consistent approaches of observation targeting and data assimilation using adjoint techniques," *Geophys. Res. Abstr.,* vol. 5, 06185, 2003.

[5] Y. Zhu and R. Gelaro, "Observation sensitivity calculations using the adjoint of the Gridpoint Statistical Interpolation (GSI) analysis system," *Mon. Wea. Rev.*, vol. 116, pp. 335-351, January 2008.

[6] R. Gaston and E. Rodriguez, "QuikSCAT follow-on concept study," JPL Publication 08-18, April 2008. [Available on-line at http://winds.jpl.nasa.gov/publications/QFO_MissionConceptReport_JPL_08-18_2.pdf].

[7] P. Kangaslathi, D. Pukala, T. Gaier, and S. Brown, "Broadband receiver technology for atmospheric humidity, temperature and precipitation sounding," unpublished. [Presented at 2008 Earth Science Technology Conference, University of Maryland University College, 24-26 June 2008; available on-line http://esto.nasa.gov/conferences/estc2008/papers/Kangaslahti_Pekka_B2P3.pdf]

[8] D. W. Hillger, "GOES-R Advanced Baseline Imager color product development," *J. Atmos. Oceanic Tech.*, vol. 25, pp. 853-872, June 2008.

[9] S. Q. Kidder et al., "Satellite analysis of tropical cyclones using the Advanced Microwave Sounding Unit (AMSU)," *Bull. Amer. Meteor. Soc.*, vol. 81, pp. 1241-1259, June 2000.

[10] M. M. Gierach, M. A. Bourassa, P. Cunningham, J. J. O'Brien, and P. D. Reasor, "Vorticity-based detection of tropical cyclogenesis," J. Appl. Meteor. Climatol., vol. 46, pp. 1214-1229, August 2007.

[11] S. A. Wood, G. D. Emmitt, L. S. Wood, and S. Greco, "Doppler Lidar Simulation Model Version 4.2 online Web-based User's Guide," unpublished. [Available on-line at http://www.swa.com/ald/DLSM4.2/index.htm].

[12] J. Graf et al., "NASA scatterometer experiment," *Asta Astronaut*, vol. 43, pp. 397-407, 1998.

[13] J. Figa-Saldana et al., "The advanced scatterometer (ASCAT) on the meteorological operational (MetOp) platform: A follow on for European wind scatterometers," *Can. J. Remote Sensing*, vol. 28, pp. 404-412, 2002.

[14] K. Hilburn, D. K. Smith, and F. J. Wentz, "Rain effects on scatterometer systems," unpublished. [Presented at NASA Ocean Vector Wind Science Team Meeting, May 18-20, 2009, Boulder, Colorado; slides available on-line at http://coaps.fsu.edu/scatterometry/meeting/docs/2009_may/rainissues/hilburn.pdf]

[15] L. Jones and P. Laupattarakasem, "QSCAT hurricane wind vector simulation for HIRad OSSE," unpublished. [Available from the Central Florida Remote Sensing Lab, written 2007.]

[16] C. O'Handley, G. D. Emmitt, and S. Greco, "Simulating cloud motion vectors from global general circulation model data for use in OSSEs: A preliminary, but useful, algorithm for application to current NASA/NOAA OSSE projects," unpublished. [Available from Simpson Weather Associates, written October 2001.]

[17] C. O'Handley and G. D. Emmitt, "Further development of an algorithm for simulating cloud motion wind vectors from global general circulation model data," unpublished. [Available from Simpson Weather Associates, Inc., September 2002.]

[18] National Oceanic and Atmospheric Administration (NOAA), National Environmental Satellite Service (NESDIS), "GOES-R Series Concept of Operations (CONOPS)", March 2009; P417-R-CONOPS-0008, Version 2.4.