APPENDIX C

NATIONAL SECURITY SPACE ARCHITECT SPACE WEATHER ARCHITECTURE

C.1 Introduction

The Space Weather Architecture was developed using the NSSA standard architecture study development process. The Space Weather Architecture Study Terms of Reference (TOR), 4 December 1997, directed the NSSA to lead an integrated Space Weather Architecture Study with Department of Defense (DOD), National Aeronautics and Space Administration (NASA), National Oceanographic and Atmospheric Administration (NOAA), and other agency participation. Accordingly, the NSSA formed a Space Weather ADT composed of representatives from major stakeholders. The ADT assessed the current environment and projected one 15-25 years in the future to understand how space capabilities may be used.

The Space Weather Architecture Study was conducted in two phases. Phase I determined that an architecture study was warranted and gathered the information necessary to conduct it. Phase II developed and analyzed architecture alternatives, and generated space weather architecture findings and recommendations. These key study findings and recommendations are listed below. The NSSA study results are consistent with the NSWP recommendations and reflect a more in-depth review of the 2010+ user needs, support of national priorities, and consider fiscal resource limitations.

After study completion, the NSS SSG endorsed an Architecture Guidance Memorandum that identified the Office of the Assistant Secretary of Defense for Command, Control, Communications, and Intelligence (OASD(C3I)), in coordination with NOAA, as the overall agency responsible for overseeing a Space Weather Transition Team, composed of key space weather stakeholders. A Space Weather Transition Team was organized to develop a plan to provide guidance on implementing the approved recommendations. The NSS SSG also provided direction in an Architecture Implementation Memorandum on implementing the Space Weather Transition Plan.

Periodic progress reviews of the Space Weather Architecture Transition Plan will be required over the coming years. The interagency coordinating structure of the NSWP Council and the CSW will provide the vehicle to assess the state of progress, adjust the direction of the program to match breakthroughs in technology or changes in requirements, and to resolve conflicts between or among the stakeholder agencies.

C.2 Key Study Findings and Recommendations

C.2.1 Space Weather Architecture Vector

To guide future investment, development and acquisition of space and space-related capabilities, the NSSA recommends:

- **Increase emphasis on Operational Model development**
- **Ensure improved Operational Capabilities based on User Needs**
  - **National Security priorities include Ionospheric and Radiation Environment Specifications and Forecasts**
  - **Civil priorities also include Geomagnetic Warnings and Forecasts**
- **Evolve to improved Forecast Capabilities, as phenomenology is better understood, models mature, and user needs are better defined**

Future National Security operations will require improved capability to accurately locate targets, provide precision navigation, and provide reliable mobile communications in a more time-constrained environment. To support these capabilities, immediate emphasis must be given to the accurate specification and forecasting of ionospheric total electron content (TEC) and scintillation parameters. It is essential that ground-based and space-based ionospheric observing systems and ionospheric models be developed and employed expeditiously. Also, significant to National Security is the capability to determine rapidly whether space weather or an adversary is degrading critical satellites. In addition, it is important to design robust satellites and rapidly recover damaged satellites. To support these needs, it is necessary to develop and employ systems and models to provide an essential capability to specify the radiation environment at satellite altitudes. The desired capability also includes forecasting of the radiation environment at satellite altitudes.

Like National Security needs, civil needs also include ionospheric and radiation specification and forecast. In addition, the civil community places priority on geomagnetic forecasting through in-situ solar wind measurements. These capabilities will significantly enhance the civil community's capability to support the power industry mitigation of losses from outages, and NASA's ability to protect astronauts from harmful radiation effects.

These recommendations are based on analysis of architectural alternatives. Because of the criticality of models to improved space weather architecture performance, these architectural alternatives have a common set of forecast and specification models. In addition, a common concept of operations (CONOPS) and communications systems were defined. Each alternative was designed to provide maximum benefit-cost ratio at its projected funding level.

One alternative represents a minimal capability. The sensor emphasis was on solar flare and Coronal Mass Ejection (CME) imaging and on providing a dense measurement grid of ionospheric properties and magnetospheric particles and fields. This alternative provides high quality specifications in all domains of interest such as ionospheric electron density, equatorial scintillation and neutral density, and solar event forecasts.

The second and target level, adds magnetic field and particle sensors near the L_1 position to directly sample the solar wind and the CMEs about one hour prior to their hitting the magnetosphere. The L_1 sensor adds confidence to ionospheric electron density, magnetospheric particles and fields and neutral density specifications, and improves polar scintillation, magnetospheric particles and fields forecasts.

The next level of development represents a more desired robust capability adding a second CME imager. It provides a more side-on view to better characterize evolution and minimize false alarms. It will improve longer-term forecasts of magnetospheric particles and fields, Van Allen Belt radiation, ionospheric properties, and neutral density.

Even this alternative is not expected to satisfy all the 2010-2025 needs, particularly forecast needs. Considering the likely technology and basic research and development necessary for space weather models implementation, this alternative is the best we can likely achieve during this timeframe.

These architecture concepts identified and pointed to the investments which would yield the most timely benefit. Specifically, the desired goal of achieving the capabilities represented by the most enhanced alternative must evolve from the minimal capability through the first level of enhancement as resources allow. To provide these capabilities, an integrated systems acquisition approach (e.g., sensors, processing systems, models, and products) focused on user needs is required.

Fiscal constraints demand prioritization of expenditures. The study identified the need for some increased investments. The highest leverage near-term investment was found to be validated, reliable space weather operational models. To achieve these models, a robust focused R&D effort is needed, including the continuation of science missions to collect data required by researchers for developing model algorithms. Operational data collection must provide increased sensor coverage and be archived to serve as a basis for model validation. This archive should be expanded to include correlated space weather impacts supporting system acquisition, simulation and operational planning.

This recommended architecture vector provides a user oriented approach, consistent with the OFCM plans. It will allow a smooth transition to the future national space weather infrastructure.

In summary, the ADT found:

- The Current Baseline supports limited model-development
- Primary space weather support future user systems needs are: Improved Ionospheric TEC & Scintillation and Radiation Environment specifications and forecasts
- Users desire continuously updated impact oriented products
- Increased investment in and dependence on space systems (military, civil, and commercial) justifies some increased space weather investments

C.2.2 Space Weather Importance Awareness

To guide future investment, development and acquisition of space and space-related capabilities, the NSSA recommends:

- **Integrate Space Weather information (system impacts and space weather environment data) into User Systems through inclusion in:**
  - **User Education**
  - **Simulations**
  - **Wargaming and Training**
  - **CONOPS**
  - **Contingency Planning**
  - **System Anomaly Resolution**
  - **Damage Assessment and Reporting**

National Security dependence on space support is increasing dramatically but the number of National Security satellites is expected to remain relatively constant with less backup and residual capability. Civil and commercial dependence on space systems is also increasing. Under these circumstances, each satellite is more critical and satellite outages will have greater impacts. The National Security demand for commercial SATCOM (e.g., hand-held terminals) will increase, creating new unpredictable vulnerabilities.

The study found limited design information and guidelines for many new orbits. Furthermore, commercial competitive pressures to cut satellite development costs lead to reduced testing and away from military hardening. The developers of user systems must be aware of potential space weather impacts through user education and space weather inclusion in Simulation Based Acquisition (SBA).

In the past, space systems have been part of the support (force enhancement) infrastructure. In the future, terrestrial weapons are likely to be directly targeted using space, and some weapons may be space-based. This will drive an increase in coverage, timeliness, accuracy, and command and control assuredness requirements for space systems. Space weather can significantly impact the ability to achieve needed levels of capability. For example, ionospheric scintillation can disrupt access to the Global Positioning System (GPS) and to radar signals with uncertainty in the ionospheric electron density degrading geolocation accuracy. Today, outage causes are often not precisely determined, leading to less effective mitigation, and recovery. This lack of understanding also impacts user system and space weather model design improvements.

Space weather fidelity in Service wargaming is seriously deficient. In essence, space weather is ignored. Better simulation of space weather effects in wargaming will increase space weather awareness in the user community and allow for development of mitigation and exploitation strategies.

In summary, the ADT found:

- Operators frequently do not understand space weather impacts. Consequently to reduce operational risks, space weather education and training is critical
- Space weather information needs to be integrated into all phases of system life cycles
- Budget and competitive pressures on satellite providers coupled with expected increases in demand for improved coverage, timeliness, accuracy and assuredness for

space-based services, increase the potential impact of future space weather perturbations

- Space weather effects have the most impact on communications, position finding, navigation, timing, intelligence, surveillance, and reconnaissance

C.2.3 Space Weather Requirements

To guide future investment, development and acquisition of space and space-related capabilities, the NSSA recommends:

- **Develop a set of Approved Validated Space Weather Requirements focused on User Needs**
- **Update Requirements as User Needs and Technology evolve**

An effective space weather architecture depends on better understanding and documentation of user needs to provide compelling justification of what is needed and at what priority. Needs definition for the space weather study started with the draft AFSPC space weather CRD and the OFCM NSWP Strategic and Implementation Plans. Joint Vision 2010 was reviewed and its implementing systems evaluated for space weather susceptibility. Further understanding came from review of current architecture requirements and projected needs for a wide range of users. In addition, the User Applications Tiger Team systematically reviewed all classes of users (i.e., National Security, civil, and commercial) and their projected space weather impacts and product needs.

A space weather space architecture exercise (SAX) captured operators and planners opinions of user needs and potential user responses. This exercise examined the needs for product user interface, timeliness, and accuracy in several user system scenarios with space weather impacts. The results confirmed the need for a clearer definition of the requirements for the space weather architecture in user impact terms.

National Security users have a driving need for improved product confidence, accuracy, resolution, and coverage. Observations and measurement refresh rates must be increased to improve timeliness. Enhanced modeling and analysis techniques and rigorous validation will elevate forecast confidence. Improvement of product timeliness requires an enhanced capability to receive, process, and display space weather information.

In summary, the ADT found:

- Current requirements for space weather products are outdated, fragmented and incomplete
- Military and civil space weather requirements are similar but often addressed independently
- Insufficient understanding of user priorities and requirements causes significant gaps in current capabilities and has hampered efficient acquisition
- Space weather effects need to be translated into user impacts and evaluated for potential mitigation techniques

- Lack of users understanding of space weather impacts on operations has impeded development of accurate space weather requirements
- Requirements must be revised as user needs and technology evolve

C.2.4 Coordinated Space Weather Architecture Acquisition

To guide future investment, development and acquisition of space and space-related capabilities, the NSSA recommends:

- **Identify a cognizant organization in DOD to:**
  - **Manage the Acquisition of DOD Operational Space Weather Architecture and focus DOD Space Weather Research and Development**
- **Ensure Validated Models are developed in conjunction with Sensors and User Needs**
- **Ensure effective transitioning of R&D into Operations**
  - **Coordinate Acquisition and Integration of Space Weather Resources across Civil agencies and National Security Interest**

Needs for higher confidence user-friendly products are expected to grow. Model improvement is essential to increased specification and forecast confidence and performance.

Currently, the operational models are acquired from multiple sources—directly from R&D labs and universities, commercially, and through acquisition organizations. They supply products with differing or unknown levels of confidence. Sometimes the models have not been validated before quasi-operational implementation.

Historically space weather sensors were often fielded independent of the operational models or were not a-priori designed to work with operational models. A coherent user needs focus will lead to an improved space weather architecture performance.

The longest lead items for the architectures were found to be the models. This study identified and traced models to needed sensor inputs. It appears that efficiencies can be achieved by coordinating development of models between civil and National Security sectors. Within DOD, a single acquisition manager for the DOD portions of the space weather architecture can be achieved. To be most effective, space weather acquisition coordination needs to be performed at an interagency level.

In summary, the ADT Found:

- Military, civil, commercial and international cooperation will provide opportunities for cost and data sharing
- Cross-agency coordination is required to achieve improved model performance with validated model development prioritized to keep pace with sensor development
- Operational models, sensors and products can benefit from an integrated development approach
- The lack of a controlled process for model development and validation has led to inconsistencies in performance and confidence of models

C.2.5 Space Weather Information Archive

To guide future investment, development and acquisition of space and space-related capabilities, the NSSA recommends:

- **Consolidate and Expand the Existing Archival System**
  - **Capture Space Weather Environmental Data and System Impacts**
- **The Archival System should be:**
  - **Centrally Managed**
  - **User Focused**
  - **Incorporate Standard Formats**
  - **Accommodate Multi-level Security**

Spacecraft developers, insurance agencies, HF communicators, third party vendors, and power companies in the commercial sector responded to the space weather Architecture Study Request For Information. They provided insights into the needs for improved archiving.

(a) The commercial satellite builders are interested in historical space weather information (e.g., high, low, and average environments) to improve future satellite designs.

(b) Industry knows that design lessons are often relearned due to the long eleven year solar cycle and personnel turnover. Industry is increasing the pressure for reduced satellite development time and decreased testing time.

(c) Insurance rates currently do not reflect the space weather robustness of satellite systems, but interest was expressed in knowing the statistics of space weather events and impacts.

During the definition of user needs, the ADT determined that a significant number of space weather products must have high confidence. This requires that the models used to produce products be validated against the real world (i.e., historical space weather data (climatology) from multiple solar cycles and global coverage).

The difficulties of collecting validated space weather impacts on operational systems during Phase I pointed to the need for a centrally managed and standardized repository to capture impact information. Space weather impacts are often misidentified as other types of anomalies, increasing diagnosis time and thus the time to mitigate. These needs may be met by a centralized user-friendly data resource for researchers, space weather model developers, user system designers, planners and wargamers. It should capture space weather effects (start time, duration, and intensity), space weather climatology, and user system impacts.

In summary, the ADT found:

- Space weather effects and their operational impacts are not well documented—improved archiving of both would benefit research, operations, acquisition, analysis, simulation and wargaming
- Data that can be used to validate models and products is key to producing high confidence products
- Industry is interested in space weather design guidelines built on space weather climatological data

- Space weather impacts and environmental data are essential to understanding space weather trends

C.2.6 Integrated User Information

To guide future investment, development and acquisition of space and space-related space weather capabilities, the NSSA recommends:

- **Provide Space Weather Information:**
  - **In User Impact Terms**
  - **Routinely Available through Common Dissemination Channels**
  - **Integrated with Other User Information as required**

In conjunction with the User Applications Tiger Team and discussions with a broad spectrum of users, a space weather SAX was conducted. The SAX objectives were to capture and assess user insight on the utility of space weather information to their planning and operations in support of a broad range of National Security and civil missions and functions.

In the area of products, the SAX results indicated that an expert system translating space weather information into user impact terms and autonomous space weather updates for correction of the user systems is needed. Users also expressed a need for standardized, integrated products and a space weather expert point of contact to be available to fill special product requests and analyses. In addition to a requirement for significant improvement in space weather specification, reliable 4-6 hour and 24-hour forecasts and advisories are needed to support the mission planning cycle.

Operational systems require high confidence space weather models. For National Security architectures, this means going through rigorous verification, validation and accreditation processes.

Increased use of expert systems and tactical decision aids (TDAs) for mission planners and operators creates a need for space weather information (not data) to be smoothly integrated with CONOPS, contingency planning and standard situational awareness displays.

The civil community has the same need for "impact" specification and forecasts as the National Security community. However, the civil community relies on a network of value added resellers to provide user specific products that use space weather assets and data.

In summary, the ADT found:

- Products currently available to operators and planners are inadequate
- Most users need space weather information provided in terms of impacts and in formats that readily integrate into existing or planned systems
- Users need high confidence in space weather products for operational decisions and medium confidence for longer term plans
- Military users expect tailored space weather products while civil policy is to provide access to basic data and rely on third party product tailoring

C.2.7 Integrated Space Weather Center

To guide future investment, development and acquisition of space and space-related space weather capabilities, the NSSA recommends:

- **Evolve to an Integrated Space Weather Center capability to include:**
  - **Space Weather Expertise available for User Consultation and Support**
  - **A National Security Support Cell to produce Tailored Products**
  - **Back-up capability to provide support in the event of Natural Emergencies or Catastrophic Equipment Failures**

One important trade axis explored was distributed — centralized processing. Performance and cost were evaluated for architectures at the extremes. Centralized processing emerged as the better approach. In addition, the need for coupled computer-intensive models using consolidated global data drove the need for a highly capable central processing facility. This facility requires access to all data sources including space weather climatology and space weather impacts. Some users will require unprocessed data and their needs can be easily met with this centralized approach.

There is a high level of cooperation between the military and civil space weather centers including sharing data, models, and personnel. However, it is clear there is a potential for cost saving by evolving to an integrated space weather support capability. Because of the unique needs of some users, a National Security cell for processing classified data or providing classified products will be needed. Space weather center integration could compromise robustness, so a back-up center must be considered to reduce vulnerability to natural disasters and catastrophic equipment failure.

During the SAX, planners and operators also expressed a need for a space weather expert to be accessible to answer space weather questions and resolve issues.

In summary, the ADT found:

- The complexity of space weather models and forecasting will likely require a full time expert resource available to produce and evaluate products and interface with users.
- Centralized processing provides a single point of contact that is best for meeting most user needs
- An integrated space weather center with civil and joint military staffing along with back-up capabilities could improve efficiency and reduce costs in developing user products
- A National Security support cell is needed to focus on tailored products and classified support for DOD and Intelligence Community users

C.2.8 Space Weather Research and Development

To guide future investment, development and acquisition of space and space-related space weather capabilities, the NSSA recommends:

- **Provide a Robust space weather Research and Development Program to:**
  - **Develop and Implement the Improved Models**
  - **Provide options for further growth**
- **Continue to Leverage Research and Development Missions**
  - **Enhance Operational Products until Operational Systems are ready**
- **Develop and Implement Standardized Processes to rapidly and efficiently Transition R&D into needed Operational Products**

A technology assessment identified, characterized, and documented a technology foundation for post-2010 space weather capabilities. Three common threads were revealed.

First, multi-point measurements are vital for a complete picture of the environment. Space weather is currently starved for data essential to global specification, improved understanding, and better initialization and validation of forecast models (e.g., measurements from space Sun-Earth-Line sensors). Today, much of the data on space weather is limited to a certain geographical area or by resolution. Thus the current space weather architecture's ability to detect and mitigate space weather impacts is severely limited.

Second, basic research is an underpinning for better models. This research should focus on coupling process physics and space weather domain specific algorithms. High confidence forecasting can only be achieved with models integrated across the space weather domains (coupling from the Sun to the magnetosphere and through the ionosphere) that are verified and validated. The processes of how and when the Sun produces CMEs and the interaction between the magnetosphere and the ionosphere must be explored.

Third, new sensors and other supporting technologies are essential, but are largely driven by other than space weather needs. These supporting technologies include automated low cost spacecraft, low cost lightweight sensors, and advanced computing to run the complex space weather models. Promising sensors like solar flare and CME imagers will move us toward the ability to predict the impact to the Earth after detection of the event on the Sun. This lead-time will improve our forecasting ability. GPS occultation sensors and combined radiation and threat warning sensors that can be inexpensively deployed on a large number of satellites and significantly contribute to specification and forecasting of the magnetosphere and ionosphere. Lightweight payloads and low integration costs are the drivers for space weather sensors riding on other types of satellites.

More data and basic research are critical to model development and improvement. The ADT also validated the current practice of leveraging R&D missions (e.g., Advanced Composition Experiment (ACE)) to provide data to forecasters that would otherwise be unavailable. The use of these data increases forecast and specification confidence.

In summary, the ADT found:

- Space weather is a technically immature discipline and basic research is vital
- R&D sensors are a valuable data source and greatly benefit data-starved operations

- Flexible space weather architecture could allow easier transition of R&D to operations
- More focus on operational needs could improve R&D pay-offs
- Some R&D is ready for transition to operations now (e.g., Coronagraph, Compact Environmental Anomaly Sensor (CEASE), and GPS Occultation)
- R&D investment is key to reducing model development risk

C.2.9 Space Weather and Man-Made Effects Information Coordination

To guide future investment, development and acquisition of space and space-related space weather capabilities, the NSSA recommends:

- **Support the Space Control Protection Mission by providing timely Space Weather Information**
- **Incorporate the Operational Specification and Forecasting of Space Environmental Effects of Man-made (Primarily Nuclear) Events as a Mission into the Space Weather Architecture**

The ADT studied the relationship between man-made effects (MME) and space weather effects on the near-Earth environment. The spatial and temporal scales of most man-made effects are smaller than those of naturally occurring space weather phenomena, while high altitude nuclear explosion energy levels can be much higher than natural phenomena as well as other MME.

MME and space weather impacts are similar for high-energy photons (e.g., x-rays), pumped radiation belts, ionospheric disturbances, and aurora emissions/clutter. Space weather sensors can be used to trace MME, but they may not have the necessary dynamic range.

The Space Control mission requires the characterization of the natural environment to differentiate between outages caused by space weather or a hostile force. In many cases it is economical to field combined packages to provide threat warning, attack assessment, and space weather (e.g., CEASE). The space weather and MME physics models are similar, and the MME models require space weather information for initialization. In addition, nuclear detonation sensors can supply useful data to space weather modelers and forecasters. Thus sharing data and models between agencies is to be encouraged.

In summary, the ADT found:

- MME are physically similar to space weather effects, differing in that MME are more localized and have different energy levels
- Nuclear effects are the primary man-made threat to the space weather environment
- Users and models would benefit from spacecraft space environmental sensors
- Nuclear detection missions collect data that could benefit the space weather mission area
- Combining space weather and threat sensors would benefit the space control mission area