# National Security Space Architect

# Space Weather Architecture Study
# Final Report

## 22 March 1999

## *Foreword*

This document summarizes the results of the National Security Space Architect Study on Space Weather, conducted 4 December 1997 to 25 January 1999.

HOWARD J. MITCHELL, Brig Gen, USAF
Director
National Security Space Architect

# Table of Contents

**SPACE WEATHER ARCHITECTURE**
**FINAL REPORT**

## BACKGROUND

National Security operations and the national economy increasingly rely on space and ground systems that are susceptible to failure or degraded performance due to extreme Space Weather (SWx) conditions. SWx refers to conditions caused by the Sun and the solar wind in the Earth's magnetosphere, ionosphere, and thermosphere. SWx can adversely affect satellite operations, communications, space-based and ground-based radar, navigation, high altitude manned flight, and electrical power distribution grids. Such conditions can disrupt National Security operations and cause economic losses in both systems and services.

The SWx Architecture Study Terms of Reference (TOR), dated 4 December 1997, directed the NSSA to lead an integrated SWx 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 National Security Space Architect (NSSA) formed an Architecture Development Team (ADT) composed of representatives from major stakeholders and conducted this architecture study to develop architecture alternatives which in turn generate findings and recommendations for a future SWx architecture vector.

The Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) developed the *National Space Weather Program (NSWP) Strategic Plan* in 1995 and the NSWP *Implementation Plan* in 1997. These plans provided the vision for future national SWx sensing and forecasting capabilities and highlighted the need for an architecture-level study. The OFCM plans recommended an active, synergistic, interagency SWx architecture to provide timely, accurate, and reliable space environment observation, specification, and forecast within the next 10 years. The NSSA study results are consistent with the NSWP recommendations, reflect a more in-depth review of the 2010+ user needs, support priorities and consider fiscal resource limitations. This report documents an overview of the study methodology and results.

**STUDY OVERVIEW**

The SWx architecture study was conducted in two phases (Figure 1). 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 SWx architecture findings and recommendations. After study completion, a Transition Team, composed of stakeholder representatives, will develop a plan to implement the approved recommendations.

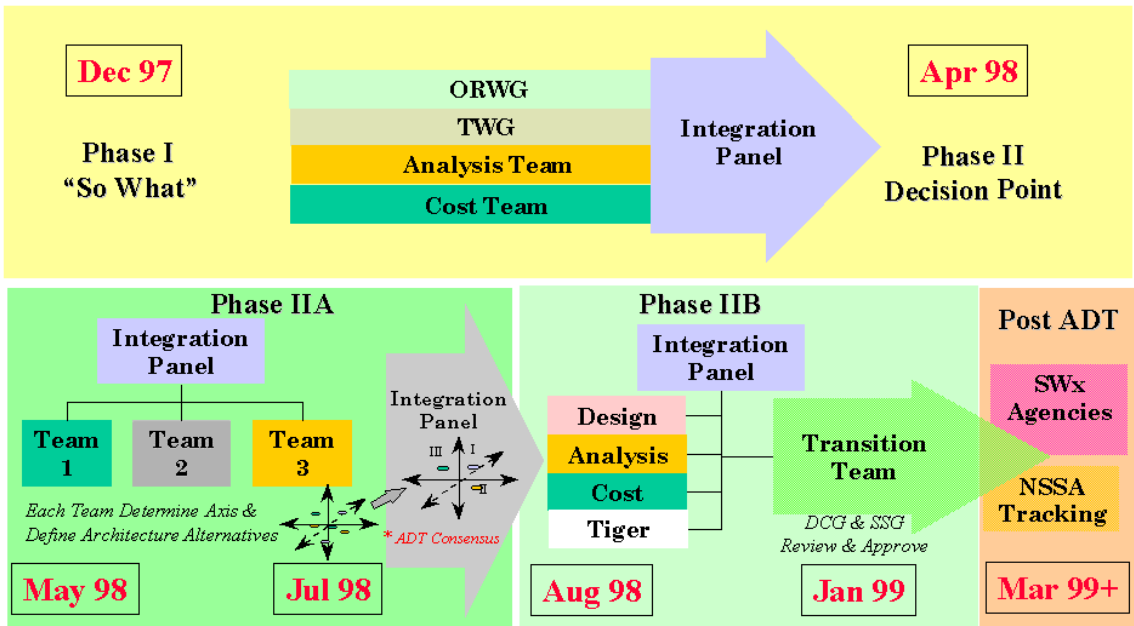


*Figure 1: Space Weather Study Overview*

***<u>SWx Architecture Study Phase I</u>***

Phase I answered four questions.

1. Does SWx impact National Security Objectives?
2. Does the Evolved Baseline provide needed capability?
3. Will technologies be available to provide projected needed capability?
4. Can Phase II provide viable SWx Architecture Alternatives?

To answer the first question, planners from the Services, the Joint Staff, and other organizations were consulted and planning documents reviewed to identify future National Security and civil systems and how those systems would be used.

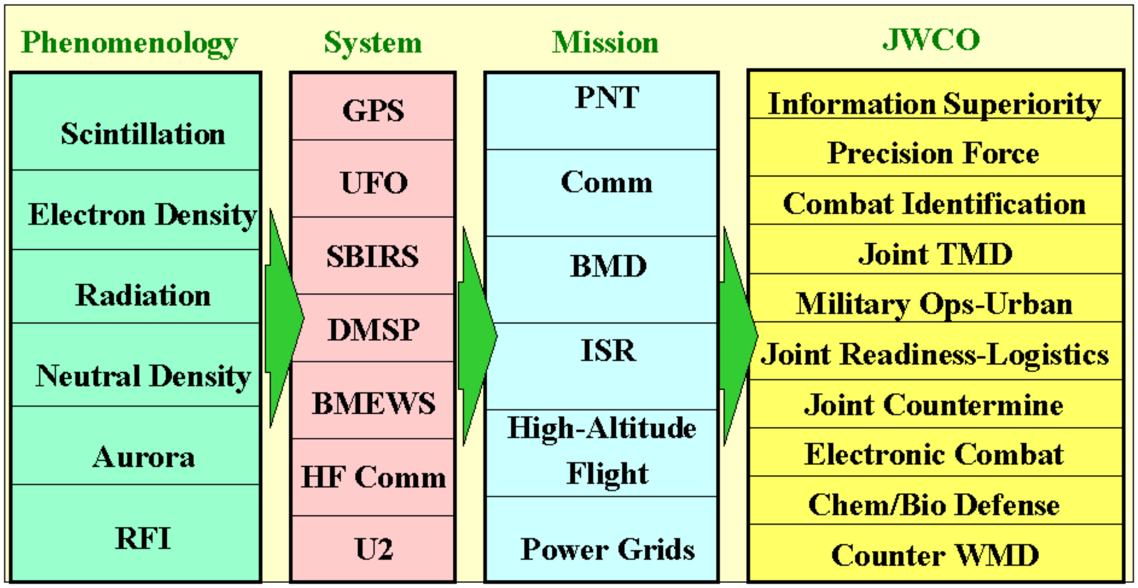


*Figure 2: Operational Impacts Joint Warfighting Capability Objectives*

Current and future systems were assessed for SWx vulnerabilities and the expected effects were mapped into impacts on Joint Vision 2010 Joint Warfighting Capability Objectives (Figure 2). The results clearly showed that SWx does impact National Security objectives. This assessment was validated by examining instances of SWx impacts on past and current systems and supported by quantitative analysis for selected cases.

To answer the second question, the current operational SWx architecture (current baseline) was identified. By examining current plans, the ADT developed the expected SWx architecture 2010 baseline, termed the Evolved Baseline (EB). Starting with Air Force Space Command (AFSPC) draft Capstone Requirements Document (CRD), other system Operational Requirements Documents (ORDs) and civil requirements identified by NOAA, the ADT projected a set of future SWx needs.

The ability of the current baseline to meet future needs was assessed and shortfalls were identified (Figure 3). The products assessed were specification, forecast and warning. A specification refers to the fusion of all available observations into a coherent and realistic representation of the state of the space environment, at a particular point in time. A forecast is a prediction of space environment conditions for a given time period. A warning is a forecast of a hazardous space weather event that requires some immediate user action. It became clear that the current baseline fell short of meeting needed capabilities for the future users.

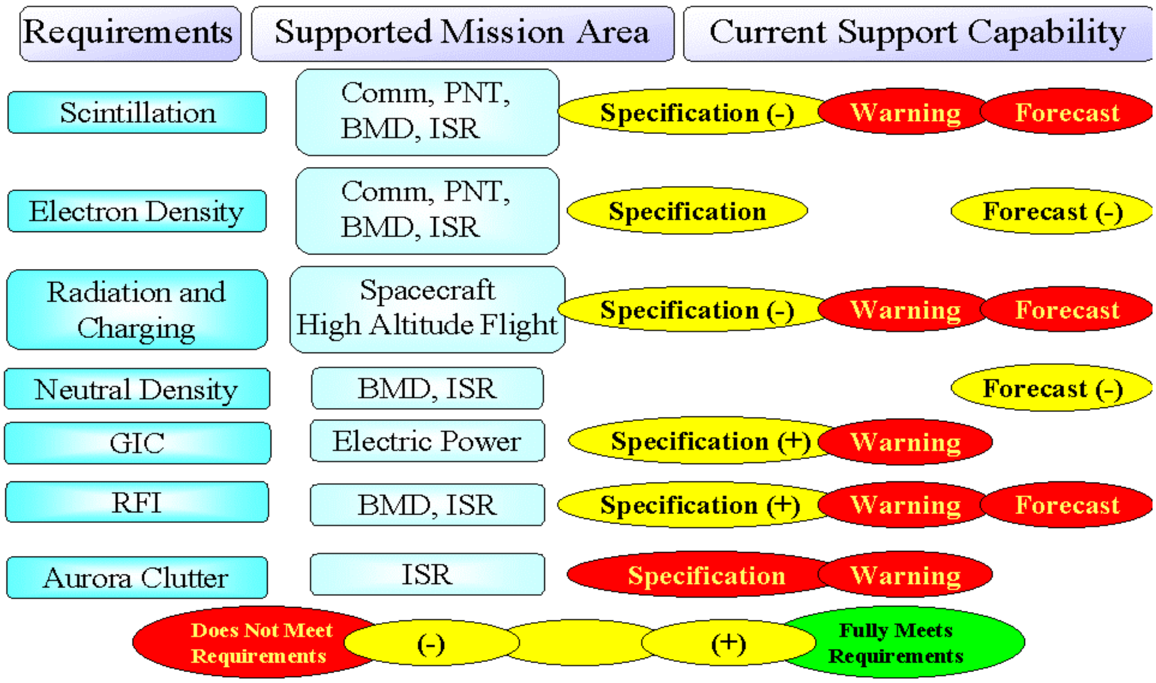


*Figure 3: Current Baseline Assessment*

To answer the third question, the Technology Working Group (TWG) addressed technology capability. They identified the technologies and basic research that could lead to an enhanced SWx capability. Relevant technologies included new and improved sensors, improved models, and general technologies aimed at lower cost and higher performance spacecraft, communications, and computing.

The fourth question addressed the potential for improvement through proceeding with Phase II. The TWG identified that we are on a "Technology Cusp" where there is the potential that SWx support can move from a monitoring service to a predictive service. SWx stakeholder organizations expressed a strong desire for a SWx Architecture to focus technology and modeling into developing operational capabilities. The stakeholders, through a Decision Coordination Group (DCG) meeting, decided that it was possible to develop viable SWx Architecture Alternatives and they recommended that the study proceed.

***SWx Architecture Study Phase II***

In Phase II, the ADT developed architecture alternatives for evaluation leading to recommendations supporting National Security and other national needs for the 2010 to 2025 timeframe. The recommendations are statements of prioritized capabilities to be acquired and include top level guidance on investments necessary to achieve the needed capabilities. These recommendations will be used by the Transition Team post-ADT to develop a plan and implementing directives to guide research, technology investment, acquisition planning, program execution, and future operations planning between now and 2010.

Phase II was conducted in two parts. In Phase IIA, the ADT determined major architecture drivers and chose a trade space used to describe major architecture variations. The team then constructed a set of architecture alternatives, which fully explored that trade space and carefully assessed these alternatives (Figure 4).

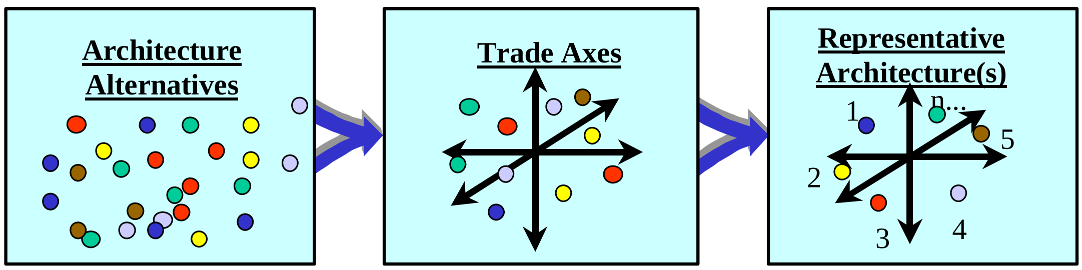


*Figure 4: Phase II A Architecture Alternative Development Process*

The architectures were developed with the C4ISR Architecture Framework Version 2 as guidance. Architecture Alternative Working Groups (AAWGs) accomplished this construction. These groups were composed of NSSA staff and stakeholder representatives, most of whom had participated in Phase I. Each AAWG had responsibility to brainstorm architectures that addressed future needs. These architectures were described at a fairly high level of abstraction by using tailored versions of the Overview and Summary Information (AV-1), High Level Operational Graphic (OV-1) and Operational Node Connectivity Diagram (OV-2), and were evaluated qualitatively in terms of pros and cons. These partial architectures and their implied trade axes were integrated and assessed. The result was a set of key trade axes and thirteen candidate architectures. Each of the alternative architectures was mapped into the trade space in order to capture essential architectural elements. The key trade axes were sensor location (ground – space), user products needs (observation – forecast), and SWx processing (distributed – centralized).

The User Application Tiger Team refined the Phase I set of future National Security and civil SWx needs. The SWx products needed to survive, adapt, mitigate, and exploit SWx impacts on user and enemy systems were captured. The Tiger Team reviewed Launch; Satellite Operations; Position, Navigation, and Timing (PNT); Intelligence, Surveillance, and Reconnaissance (ISR); Radar; Manned Flight; Space Control and Ballistic Missile Defense mission areas. The team found that the military user needs autonomous updating of SWx information into system operations. In addition, where appropriate, SWx information needs to be fused with other information, creating tailored decision-ready products. The military user expects SWx products and expertise to be easily locatable through a single source.

Industry views were invited via a Request for Information (RFI) in the Commerce Business Daily. Subsequent meetings and industry briefings included satellite designers and builders, space insurance, and electrical power industry representatives. They provided additional insight into SWx impacts and needs. Finally, issue teams for Man-Made Effects (MME) and Meteorite/Debris were formed to determine potential synergism with the SWx architecture.

The MME Team identified synergy between MME impacts, models and potential sensor suites. The Meteorite/Debris team also identified synergy but only regarding data archiving.

In Phase IIB, design, analysis, and cost teams composed of government and industry experts were established. The Design Team fleshed out the AAWG alternative architecture concepts with sensors, platforms, models, information processing, communications, staffing, and logistics details using the C4ISR Architecture Framework System Interface Description (SV-1). They provided nine architecture “point designs” spanning the trade space. These “point designs” were assessed by the Analysis Team using performance (value), robustness (operational risk), and technical risk. The Cost Team evaluated these “point designs” using standard DoD and NASA approved costing methodologies.

The performance assessment employed the value methodology used by the Air Force *2025* study and other major studies to assess architecture worth. The value model tool captured the future user needs and their importance to stakeholders as weightings. At the product level, the expected performance of each architecture was scored. The scores and weightings were combined to produce an overall value based on user needs. This work served as the basis of the cost – benefit evaluation of the alternative architectures (Figure 5).

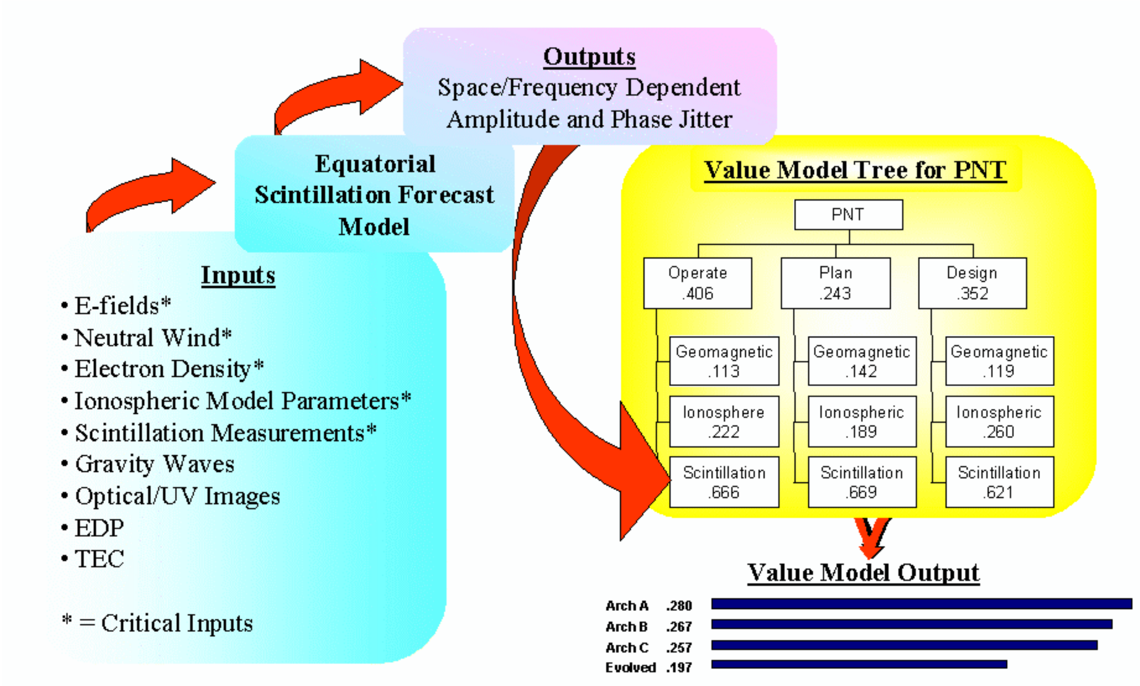


*Figure 5: Value Model Evaluation Process*

During this phase of the study, a Space Architect Exercise (SAX) was conducted. The SAX results identified specific SWx characteristics and architecture capabilities important to the National Security and civil communities and confirmed the most critical aspects of a National SWx architecture.

The SAX defined three timeframes for the scenarios (Table 1). Scenario #1 was identified as the immediate impacts (0 to 12 hours) from a major solar event. Scenario # 2 addressed delayed impacts (72 to 144 hours) and Scenario # 3 represented the undisturbed solar conditions (after 7 days).

The systems and identified effects are:

| Scenario | System | SWx Phenomenon | Operational Impact |
|---|---|---|---|
| 1 | **International Space Station** | **Radiation** | **Human Radiation Exposure** |
| 1 | **Fire Support System HF Comm** | **Ionosphere** | **Signal Fade** |
| 1 | **SBIRS High** | **Radiation** | **Spacecraft Charging/Loss** |
| 2 | **Navy Radar AEGIS SPY-1** | **TEC** | **Target Position Error** |
| 2 | **Space Based Microwave Weapon** | **Radiation** | **Masked Attack** |
| 2 | **Advanced SHF MILSATCOM** | **Radiation** | **Spacecraft Charging/Loss** |
| 2 | **Single Frequency GPS Receiver** | **TEC** | **Inaccurate Location** |
| 2 | **Northeast Power Grid** | **Geomagnetic Storm** | **Power Grid Failure** |
| 2 | **Commercial Space Plane** | **Neutral Density** | **Flight Profile Change** |
| 2 | **SBIRS Low** | **Auroral Emissions** | **Target Acquisition Delay** |
| 3 | **Cellular Comm Satellite Network** | **Scintillation** | **Signal Disruption** |
| 3 | **Bistatic Radar** | **Scintillation** | **Signal Disruption** |

*Table 1: SAX Scenario Definition*

The SAX information was subsequently employed in the architecture development effort.

Through iterative re-design and re-analysis (technical and cost), the ADT formulated key findings and recommendations and distilled the analytical results into an architecture vector responsive to future National needs.

Upon approval of the SWx architecture recommendations by the National Security Space Senior Steering Group (NSS-SSG), ASD (C3I) will lead a Transition Team to develop a Transition Plan that addresses the necessary implementation actions.

## KEY STUDY FINDINGS AND RECOMMENDATIONS

***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 SWx 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 SWx 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 SWx 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 SWx 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 SWx 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 SWx infrastructure.

In summary, the ADT found:

- The Current Baseline supports limited model-development
- Primary SWx 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 SWx investments

***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 SWx impacts through user education and SWx 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. SWx 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 SWx model design improvements.

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

In summary, the ADT found:

- Operators frequently do not understand SWx impacts. Consequently to reduce operational risks, SWx education and training is critical
- SWx 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 SWx perturbations

- SWx effects have the most impact on communications, PNT, and ISR

***<u>Space Weather Requirements</u>***

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 SWx 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 SWx study started with the draft AFSPC SWx CRD and the OFCM NSWP Strategic and Implementation Plans. Joint Vision 2010 was reviewed and its implementing systems evaluated for SWx 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 SWx impacts and product needs.

A SWx 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 SWx impacts. The results confirmed the need for a clearer definition of the requirements for the SWx 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 SWx information.

In summary, the ADT found:

- Current requirements for SWx products are outdated, fragmented and incomplete
- Military and civil SWx 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
- SWx 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 SWx requirements
- Requirements must be revised as user needs and technology evolve

***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 SWx 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 SWx 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 SWx architecture can be achieved. To be most effective, SWx 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

***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 SWx Architecture Study Request For Information. They provided insights into the needs for improved archiving.

(a) The commercial satellite builders are interested in historical SWx 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 SWx robustness of satellite systems, but interest was expressed in knowing the statistics of SWx events and impacts.

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

The difficulties of collecting validated SWx impacts on operational systems during Phase I pointed to the need for a centrally managed and standardized repository to capture impact information. SWx 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, SWx model developers, user system designers, planners and wargamers. It should capture SWx effects (start time, duration, and intensity), SWx climatology, and user system impacts.

In summary, the ADT found:

- SWx 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 SWx design guidelines built on SWx climatological data
- SWx impacts and environmental data are essential to understanding SWx trends

***Integrated User Information***

To guide future investment, development and acquisition of space and space-related SWx 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 SWx SAX was conducted. The SAX objectives were to capture and assess user insight on the utility of SWx 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 SWx information into user impact terms and autonomous SWx updates for correction of the user systems is needed. Users also expressed a need for standardized, integrated products and a SWx expert point of contact to be available to fill special product requests and analyses. In addition to a requirement for significant improvement in SWx specification, reliable 4-6 hour and 24-hour forecasts and advisories are needed to support the mission planning cycle.

Operational systems require high confidence SWx 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 SWx 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 SWx assets and data.

In summary, the ADT found:

- Products currently available to operators and planners are inadequate
- Most users need SWx information provided in terms of impacts and in formats that readily integrate into existing or planned systems
- Users need high confidence in SWx 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

***Integrated Space Weather Center***

To guide future investment, development and acquisition of space and space-related SWx 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 SWx climatology and SWx 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 SWx centers including sharing data, models, and personnel. However, it is clear there is a potential for cost saving by evolving to an integrated SWx 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. SWx 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 SWx expert to be accessible to answer SWx questions and resolve issues.

In summary, the ADT found:

- The complexity of SWx 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 SWx 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

***Space Weather Research & Development***

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

- **Provide a Robust SWx 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 SWx capabilities. Three common threads were revealed.

First, multi-point measurements are vital for a complete picture of the environment. SWx 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 SWx is limited to a certain geographical area or by resolution. Thus the current SWx architecture's ability to detect and mitigate SWx impacts is severely limited.

Second, basic research is an underpinning for better models. This research should focus on coupling process physics and SWx domain specific algorithms. High confidence forecasting can only be achieved with models integrated across the SWx 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 SWx needs. These supporting technologies include automated low cost spacecraft, low cost lightweight sensors, and advanced computing to run the complex SWx 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 SWx 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:

- SWx 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 SWx 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

***Space Weather and Man-Made Effects Information Coordination***

To guide future investment, development and acquisition of space and space-related SWx 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 SWx effects on the near-earth environment. The spatial and temporal scales of most man-made effects are smaller than those of naturally occurring SWx phenomena, while high altitude nuclear explosion energy levels can be much higher than natural phenomena as well as other MME.

MME and SWx impacts are similar for high-energy photons (e.g., x-rays), pumped radiation belts, ionospheric disturbances, and aurora emissions/clutter. SWx 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 SWx or a hostile force. In many cases it is economical to field combined packages to provide threat warning, attack assessment, and SWx (e.g., CEASE). The SWx and MME physics models are similar, and the MME models require SWx information for initialization. In addition, nuclear detonation sensors can supply useful data to SWx modelers and forecasters. Thus sharing data and models between agencies is to be encouraged.

In summary, the ADT found:

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

## SPACE WEATHER ARCHITECTURE STUDY CONCLUSION

The nine recommendations of the SWx architecture study are intended to put the United States on a path to a robust, capable SWx specification and forecasting capability. They offer an integrated, cohesive program that maximizes resources and eliminates, to the extent possible, parallel efforts. This will require a high level of cooperation within the space weather community. In order to implement these recommendations, further work is needed.

The first task is stakeholders' acceptance of the SWx architecture Transition Strategy. The transition strategy, developed by NSSA in coordination with stakeholders, will guide mid-term program transition planning to achieve the recommended capabilities. The SWx transition strategy identifies key actions to be performed to transition from the current SWx support capability to the proposed SWx architecture vector.

The next task is the development of the SWx architecture Transition Plan. The SWx Transition Team will be composed of key stakeholder and user representatives led by ASD (C3I). They will build on the architecture study recommendations to achieve the desired capabilities within the transition time frames, in a measured, affordable way. The SWx architecture Transition Plan will add detail (e.g., specific milestones) to the Transition Strategy

## APPENDIX A – Study Stakeholder Organizations

OASD (C3I)
DDR&E
Joint Staff
USSPACECOM
Army Staff
CNO Staff
Air Staff
USMC Staff
AFSPC
NRO
AFMC/SMC
ONR
NRL
AFRL
BMDO
SMDC
AFOSR
DTRA
NAVSPACECOM
NOAA/OAR/SEC/NESDIS
NPOESS IPO
NASA/HQ/GSFC/JPL
USGS
DoE (LANL)
NSF

## APPENDIX B - REFERENCES


| | |
|---|---|
| SWx Architecture Study Terms of Reference (TOR) | 4 Dec 97 |
| C4ISR Architecture Framework Version 2 | 18 Dec 97 |
| Request for Information (RFI) on the *Commercial Satellites and Other Systems* in Commerce Business Daily | 6 May 98 |
| Military Requirements for Defense Environmental Satellites (MJCS 154-86) | 1 Aug 86 |
| Capstone Requirements Document (CRD) for the Space Environment Mission Area (Draft) | 4 Nov 97 |
| Mission Need Statement (MNS) for Centralized Aerospace Weather Capability (USAF MNS 003-94) | 12 Jun 95 |
| Milestone 0 Acquisition Decision Memorandum for Centralized Aerospace Weather Capability | 20 Oct 95 |
| Environmental Sensing (AFSPC MNS 035-92) | 6 Jan 93 |
| National Polar Orbiting Environmental Satellite System (NPOESS) Integrated Operational Requirements Document (IORD) | Dec 95 |
| Defense Meteorological Satellite Program (DMSP) Operational Requirements Document (ORD) | 28 Apr 93 |
| Space Weather Analysis and Forecast System USAF ORD 003-94-I/II/III-C | 1 May 97 |
| Solar Radio Burst Locator Requirements (Draft) | 14 Mar 97 |
| Technical Requirements Document (TRD) for Solar Electro-Optical Network (SEON)/Radio Solar Telescope Network (RSTN) Phase II Upgrade Technical Feasibility Program | 26 Oct 92 |
| Improved Solar Optical Observing Network (ISOON) Requirements (Draft) | 14 Mar 97 |
| National Space Weather Program Strategic Plan | Aug 95 |
| National Space Weather Program Implementation Plan | Jan 97 |

| | |
|---|---|
| Joint Vision 2010 | Undated |
| Joint Vision 2010 Implementation Plan Draft | 9 Jan 98 |
| Global Engagement: A Vision for the 21st Century Air Force | Undated |

**APPENDIX C- ACRONYMS**

| | |
|---|---|
| AAWG | Architecture Alternative Working Group |
| ACE | Advanced Composition Experiment |
| ADT | Architecture Development Team |
| AFSPC | Air Force Space Command |
| ASD (C3I) | Assistant Secretary of Defense (Command, Control, Communications and Intelligence) |
| BMD | Ballistic Missile Defense |
| BMEWS | Ballistic Missile Early Warning System |
| CEASE | Compact Environmental Anomaly Sensor |
| CME | Coronal Mass Ejection |
| Comm | Communications |
| CONOPS | Concept of Operations |
| CRD | Capstone Requirements Document |
| DCG | Decision Coordination Group |
| DCI | Deputy for Central Intelligence |
| DMSP | Defense Meteorological Satellite Program |
| DoD | Department of Defense |
| EB | Evolved Baseline |
| GIC | Ground Induced Current |
| GPS | Global Positioning System |
| HF | High Frequency |
| IC | Intelligence Community |
| ISR | Intelligence, Surveillance, Reconnaissance |
| MILSATCOM | Military Satellite Communications |
| MME | Man-made Effects |
| MMT | Micrometeoroids Tiger Team |
| NASA | National Aeronautics and Space Administration |
| NOAA | National Oceanic and Atmospheric Administration |
| NSSA | National Security Space Architect |
| NSS-SSG | National Security Space Senior Steering Group |
| NSWP | National Space Weather Strategic Plan |
| OFCM | Office of the Federal Coordinator for Meteorological Services and Supporting Research |
| ORD | Operational Requirements Document |
| PNT | Position-Navigation-Timing |
| R&D | Research and Development |
| RFI | Radio Frequency Interference |
| SATCOM | Satellite Communication |
| SAX | Space Architect Exercise |
| SBA | Simulation Based Acquisition |
| SBIRS | Space-Based Infrared System |
| SecDef | Secretary of Defense |
| SSG | Senior Steering Group |
| SHF | Super High-Frequency |

| | |
|---|---|
| SWx | Space Weather |
| TDA | Tactical Decision Aid |
| TEC | Total Electron Count |
| TMD | Theater Missile Defense |
| TOR | Terms of Reference |
| TWG | Technology Working Group |
| UFO | UHF Follow-on |