# Research to Operations Transition of an Auroral Specification and Forecast Model

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Aurorae are generally caused by collisions of high-energy precipitating electrons and neutral molecules in Earth's polar atmosphere. The electrons, originating in Earth's magnetosphere, collide with oxygen and nitrogen molecules driving them to an excited state. As the molecules return to their normal state, a photon is released resulting in the aurora. Aurora can become troublesome for operations of UHF and L-Band radars since these radio frequencies can be scattered by these abundant free electrons and excited molecules. The presence of aurorae under some conditions can lead to radar clutter or false targets. It is important to know the state of the aurora and when radar clutter is likely. For this reason, models of the aurora have been developed and used in an operational center for many decades. Recently, a data-driven auroral precipitation model was integrated into the DoD operational center for space weather. The auroral precipitation model is data-driven in a sense that solar wind observations from the Lagrangian point L1 are used to drive a statistical model of Earth's aurorae to provide nowcasts and short-duration forecasts of auroral activity. The project began with a laboratory-grade prototype and an algorithm theoretical basis document, then through a tailored Agile development process, deployed operational-grade code to a DoD operational center. The Agile development process promotes adaptive planning, evolutionary development, early delivery, continuous improvement, regular collaboration with the customer, and encourages rapid and flexible response to customer-driven changes. The result was an operational capability that met customer expectations for reliability, security, and scientific accuracy. Details of the model and the process of operational integration are discussed as well as lessons learned to improve performance on future projects.

## 1. INTRODUCTION

The Earth is constantly bombarded by particles accelerated by the Sun. In bulk, these particles are referred to as the solar wind. As the solar wind approaches Earth, it encounters the bow shock and is deflected around the magnetosphere and our planet, depending on the interplanetary magnetic field (IMF) orientation. The greater the southward orientation of the IMF, the more solar wind plasma enters the magnetosphere and penetrates deep into the neutral atmosphere near the polar regions. Transient changes in the solar wind, e.g. coronal mass ejections, disappearing filaments, high-speed streams and other eruptive events on the sun, greatly modify the solar wind and subsequently the precipitating electrons in Earth's neutral atmosphere. These highly energetic precipitating electrons collide with neutral oxygen and nitrogen molecules in Earth's polar atmosphere driving them to an excited state. As the molecules return to their normal state, a photon is released resulting in aurorae. The location of the aurorae can vary significantly depending on the solar wind velocity, the orientation of the IMF, time of day, and season.

While a spectacular sight to the human observer, the aurorae can be quite troublesome for electronic systems such as radars and radios. Radio waves experience scattering when encountering ionospheric irregularities associated with aurorae. This scattering produces clutter in radar returns [1] and noise in radio receivers [2]. Additionally, auroral activity has been shown to cause increased absorption of radio signals [3].

Because of these consequences, significant effort was aimed at determining a basic understanding of the aurora. Determination of the auroral location and intensity began with experiments using ground-based magnetometers correlated with all sky cameras [4]. The cameras detected aurora and were then correlated with the magnetometer measurements to provide an estimate of auroral location. Later, as satellite in situ measurements became routine, charged particle measurements were used to find auroral crossings to provide descriptions of the aurora [5]. This was the original Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting (OVATION) model. With the more recent development of a nearly universal solar wind – magnetospheric coupling function, solar wind and IMF measurements have been used to determine the auroral location and intensity culminating in formulation of the OVATION Prime 2013 model (OP13) [6].

In 2016, the Air Force, with funding from the Air Force Space and Missile Systems Center (SMC), embarked on a project to integrate the OVATION Prime 2013 Auroral Precipitation Specification and Forecast model into the Department of Defense’s Space Weather Operations Center. The model originated at Johns Hopkins University Applied Physics Lab (JHU/APL). The OVATION Prime 2013 model was selected from a group of models using various means to produce auroral specifications and forecasts and was chosen for its accuracy and availability of input data at the center. OVATION Prime 2013 will be used to drive other impact models within the operations center.

## 2. OVATION Prime 2013 Auroral Specification and Forecast Model

OVATION Prime 2013 is an auroral precipitation model that uses solar wind velocity and IMF as a primary driver. An optimized solar wind – magnetospheric coupling function, now called the Newell Coupling Function, is the heart of the model. In the operational implementation, the Newell Coupling Function was integrated with other components to create a complete auroral oval specification and forecasting suite for determining the location of the aurora and determining the impacts on DoD systems. Each of the major components is described in the following sections.

**Input data**

OVATION Prime 2013 uses the solar wind velocity and IMF data measured upstream of Earth, mostly at the Lagrangian point L1 approximately 1.5 million kilometers from Earth and about 148.5 million kilometers from the Sun. The model was developed using measurements from the NASA OMNIWeb OMNI2 solar wind data (https://omniweb.gsfc.nasa.gov/ow.html) between 1984 and 2005. The NASA OMNIWeb database is a compilation of solar wind data from numerous satellites including the NASA Advanced Composition Explorer (ACE) satellite which functioned as the solar wind sentinel from 1997 to present [7], the WIND satellite, and the IMPS satellite. In 2015, the NOAA Deep Space Climate Observatory (DSCOVR) was launched to maintain the solar wind observations at L1 into the future [8]. The solar wind velocity ($V_x$ - along the path between the Sun and the Earth) as well as the magnetic field components ($B_y$ and $B_z$) in geocentric solar magnetospheric coordinates are used to drive the OVATION Prime 2013 model. Newell et al. [9] experimentally determined a 4-hour history of data would produce the most accurate representation of auroral power.

**Solar Wind Propagator**

Because the input data are collected a significant distance upstream in the solar wind, the time it takes to arrive at Earth’s magnetopause is significant and must be taken into account. A solar wind propagation model provides the delay time of the measurements and determines the forecast time for arrival at Earth. This allows for a short-term forecast of the auroral location. Since OP13 was developed using the NASA OMNIWeb database, which used a solar wind propagator to determine the timing of the solar wind at the bow shock, the real-time solar wind data for the operational system must be propagated to maintain the correct relationships between solar wind and auroral forecast.

The solar wind describes the particles projected by the Sun into the solar system. On average the solar wind velocity at Earth is ~420 km/s. Due to the rotation of the Sun, the radially moving particles in the solar wind carry their associated magnetic fields outward in a spiral fashion as described by Parker [10] in wave-like patterns referenced by phase fronts or lines of constant phase. If one imagines spiral arms of the Parker spiral, these phase fronts strike the Earth at some angle that varies in time as shown in Figure 1. Taking solar wind measurements upstream in the solar wind allows a forecast of the conditions that will arrive at Earth at some point in the future. Using measurements from L1, one can achieve lead times for forecasted parameters generally 30-60 minutes in the future. However, since solar wind velocity and the phase front angles are not constant, actual propagation delay times can differ by several tens of minutes or in extreme cases of up to one hour from expected values. It is therefore imperative to select a quality propagation model to suit the needs of the downstream models dependent on the solar wind values. There are many methods to compute the delay time and some of these were evaluated for implementation [11]. The best methodology for our purposes was the "Halfway Between Model" first introduced by Richardson and Paularena [12]. They investigated the correlations of solar wind measurements from various spacecraft and found the average orientation of the plasma fronts is provided by a phase front angle of 28 degrees for the solar wind velocity and 22 degrees for the density data. Both values had an error tolerance of +/- 3 degrees. The delay time of arrival at Earth is formulated as follows:

$$\Delta \mathbf{t} = \check{\mathbf{n}}\ \mathbf{X} / \check{\mathbf{n}}\ \mathbf{V}_{sw}$$

where: X is the Earth bow shock to L1 distance and
$V_{sw}$ is the x component of the solar wind velocity measurement and
ň is the normal vector to the Parker spiral direction.

The Halfway Between Model assumes that ň lies in the GSE x-y plane and is canted on average at ~28 degrees relative to the Sun-Earth line and that phase fronts are confined to the ecliptic plane. This model ignores: 1) solar wind deceleration at 30 Earth Radii (Re) due to interaction with bow shock. Once the solar wind passes L1, the speed is assumed to be constant to the bow shock. 2) the bow shock compression due to Coronal Mass Ejections. The bow shock can compress by ~10 Re under extreme circumstances. Savani et al. [13] documented a case where the bow shock compressed from ~16 Re to ~10 Re over a period of 3 hours. This distance equals ~38,000 Km and results in approximately ~1-2 minutes of timing error for the arrival of the solar wind. This was deemed a small error and acceptable to ignore. 3) Y-component variations between the spacecraft at L1 and the Sun-Earth line. Ridley [14] evaluated the errors associated with this uncertainty in timing propagation and found timing errors of about 8 minutes when the Y separation was 30 Re or less and 17.5 to 25 minutes when the separation was 100 Re. Richardson and Paularena [12] estimated this error to be 0.26 minutes for every unit of Re separation from the Earth-Sun line which is a little higher error than Ridley's estimate but certainly reasonable.

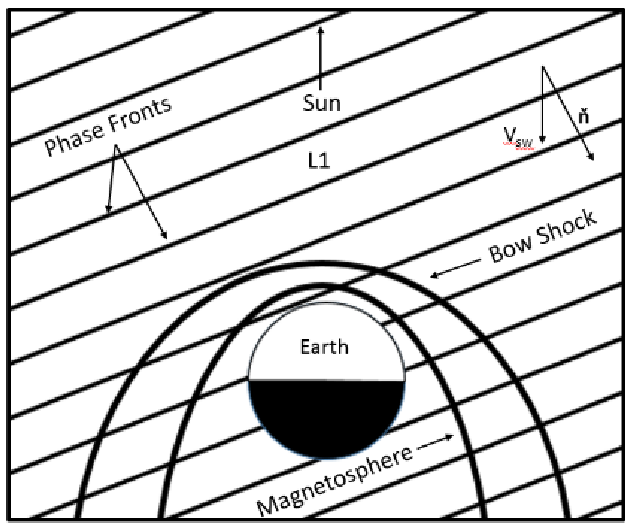

**Figure 1. Schematic diagram of the Halfway Between Model**

**Solar Wind-Magnetosphere Coupling Function**

OVATION Prime 2013 is driven by solar wind velocity and IMF observations from L1 propagated to the bow shock. To infer the solar wind effect on Earth's magnetosphere and thus the aurora, a Solar Wind-Magnetosphere coupling function, now commonly called the Newell Coupling Function, is used in the model. The function developed by Newell et al. [9] performed best of the 20 candidate functions evaluated. The coupling function is computed with:

$$\frac{d\Phi_{MP}}{dt} = \nu^{4/3} B_T^{2/3} \sin^{8/3}(\theta_C/2)$$

using the measurements of solar wind velocity ($\upsilon$), the IMF strength ($B_T = \sqrt{B_y^2 + B_z^2}$), and the IMF clock angle ($\Theta_c = \mathrm{atan}(|B_y|/B_z)$). The Newell Coupling Function uses a four-hour history of these measurements with weighting factors to allow the most recent values to primarily drive the solution.

**Computation of Auroral Power, Energy Flux, and Number Flux**

The results of the Newell Coupling Function weighted sums are then used to compute auroral energy and number fluxes for a given auroral type, magnetic local time (MLT), magnetic latitude (MLAT), and season. This formulation described in Newell et al. 2014 [6] is a set of linear relationships:

$$Auroral\ Energy\ Flux\ (auroral\ type, MLT, MLAT, season) = a + b * d\Phi_{MP}/dt$$
$$Auroral\ Number\ Flux\ (auroral\ type, MLT, MLAT, season) = c + d * d\Phi_{MP}/dt$$
$$Probability\ (auroral\ type, MLT, MLAT, season) = e + f * d\Phi_{MP}/dt$$

where b, d, and f represent slopes and a, c, and e represent y-intercepts. OVATION Prime 2013 consists of 675,840 individual regression fits for the 4 types of aurora in the flux calculations (monoenergetic, broadband, diffuse electron, and ion) and 3 types of electron aurora in the probability calculations, the 96 magnetic local time bins (at 15 minutes resolution), the 160 magnetic latitude bins (80 per hemisphere from ±50 to ±90 degrees at 0.5 degree resolution), and the 4 seasons. The individual auroral energy flux and number flux for a given grid box is the combination of the calculated flux and the probability of that auroral type occurring under those conditions (the probability equals 1 for all ion aurora). The total auroral energy flux for a given grid box is the summation over the auroral types. The total Auroral Power is the summation of all of the individual total auroral flux grid boxes weighted by their area. The number fluxes for each grid are computed in the same way with their own individual regression fits.

**Noise Reduction and Salt-and-Pepper filtering**

With so many individual regression fits, it is possible to have grid cells that differ greatly from their neighbors. Smoothing of the coefficients was performed by Newell et al. [6] to achieve a result where all grid cells return values within three standard deviations of their neighbors.

**OVATION Prime 2013 Output**

The native output of OVATION Prime 2013 is a set of images of the total auroral number flux and energy flux (energy flux is shown in Figure 2). These can be produced for individual auroral types as well.

For some applications, it is imperative to know the location of the equatorward auroral boundary. While it is discernable from the output, OVATION Prime does not natively output this key auroral characteristic in numeric form. Therefore, an algorithm was developed using the following methodology. An Auroral Mask is created by evaluating each OVATION Prime electron energy flux grid cell for presence of aurora by using a fixed threshold of electron energy flux greater than or equal to 0.2 erg/cm$^2$/sec. This mask determines cells that are deemed to contain aurora. Next, the algorithm determines the grid cells with auroral boundaries by requiring them to 1) have non-auroral neighbors and 2) have at least one auroral neighbor. Once all the cells have been identified as auroral/non-auroral they are evaluated by local magnetic time (MLT). For each 1-hour MLT the distribution of latitudes with auroral indicators are evaluated and the most equatorward latitude is determined to be the auroral boundary. Sample output is shown in Figure 2 as the red outline on the equatorward side of the aurora.

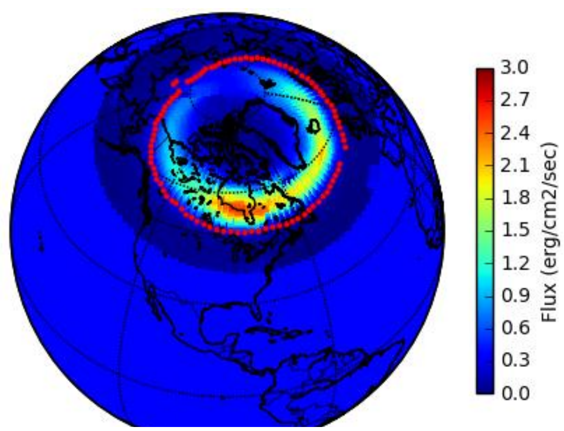


**Figure 2. Auroral Energy Flux and Auroral Boundary Algorithm output from the OVATION Prime model**

**Display**

All model outputs are sent to the United States Air Force (USAF) Air Combat Command (ACC) 557th Weather Wing for display on their web interface, AFW-WEBS. The images are displayed on a map of the Earth, using a color palette to highlight the intense portions of the aurora for military users' situational awareness.

## 3. TRANSITION METHODOLOGY

The 2015 National Space Weather Strategy [15], issued by the Executive Branch's National Science and Technology Council, establishes six strategic goals that underpin the effort to reduce the Nation's vulnerability to space weather. Goal number five states, "Improve space weather services through advancing understanding and forecasting". In outlining this goal, it states there is a need to "improve capacity to develop and transition the latest scientific and technological advances into space weather operations centers". The policy lists as an objective, "improve effectiveness and timeliness of the process that transitions research to operations". The Action Plan [16] that accompanies the strategy document states, "the ability to effectively transition research to sustained operations is a critical element for improving space weather products and services". The transition of OVATION Prime 2013 from JHU/APL to the DoD Space Weather Operations Center is in the spirit of these goals and objectives. Our effective transition methodology is described fully in this section.

Transitioning a model from the laboratory to an operational environment requires significant change from the prototype's original design. Live data, which is less timely and sometimes filled with errors, can crash an unsuspecting laboratory model without proper checks. Sharing system resources with other operational models requires good behavior on behalf of the new model. Interaction with standardized processes and other system resources requires detailed systems engineering knowledge unknown to the designers of the prototype. System security certifications and cybersecurity protections are often overlooked in the lab environment since the prototyping effort is generally about the science and not security. All these (and many other) concerns force wholesale changes in the prototype software. This change can be intimidating to the prototype developer since model validation may be impacted by changes. Managing "change" is one of the biggest hurdles in the research to operations transition. To address the Action Plan's call for an effective technology transition process, a methodology for managing change is needed.

Agile software development methods allow requirements and solutions to evolve by collaboration between cross-functional teams. It promotes adaptive planning, evolutionary development, early delivery, continuous improvement, and encourages rapid and flexible response to change. According to the Agile Alliance, the twelve principles of Agile [17] include:

- Our highest priority is to satisfy the customer through **early and continuous delivery** of a valuable system
- A **working system** is the primary measure of progress
- **Welcome changing requirements**, even late in development
- **Deliver** a working system **frequently**, from a couple of weeks to a couple of months, with a preference to the shorter timescale
- Business people and developers must **work together** daily throughout the project
- Build projects around **motivated individuals**. Give them the environment and support they need, and trust them to get the job done
- The most efficient and effective method of conveying information to and within a development team is **face-to-face conversation**
- Agile processes **promote sustainable development**
- Continuous attention to **technical excellence** and good design enhances agility
- **Simplicity**--the art of maximizing the amount of work not done--is essential
- The best architectures, requirements, and designs emerge **from self-organizing teams**
- At regular intervals, the team reflects on how to **become more effective**, then tunes and adjusts its behavior accordingly

Agile methods are about managing the impact of change, which works quite well for transitioning a model from the laboratory to an operational center. There are always unforeseen circumstances during this transition, which oftentimes lead to catastrophic results. For example, data feeding the model in the lab tends to be available consistently and of good quality. Contrast that with data collection in real time where it can be late, missing, or garbled. Data handling in these two environments should be treated in two very distinct ways. For a research to operations transition, the key is the ability to embrace change and minimize the negative impacts of that change.

Agile focuses on delivering working code by incremental development steps with short iterations. The number of completed features in the software, which is forced by practice to have an open and flexible design, measures progress of the effort. The team members are empowered to decide for themselves how best to approach the problems at hand. Personal communications are encouraged among team members as well as with the customer. Transparency is the key to success and produces trust that in the end produces a better product for the customer.

Prior to the start of a project, the Product Owner (or customer) meets with the development team. The team includes the Product Owner, the Scrum Master, a project manager, developers, and other stakeholders. They develop a release plan that determines project expectations such as “what will be delivered”, “how will the work be delivered”, “how often will deliveries be made”, and “what is the definition of done.” The answers to these questions determine the key milestones of the project and contribute to the success of the project.

Agile methods break down the process into short cycles called Sprints. Each Sprint is loaded with tasks to add functionality. Sprints are generally two to four weeks in duration. For this transition, we chose to use four-week Sprints.

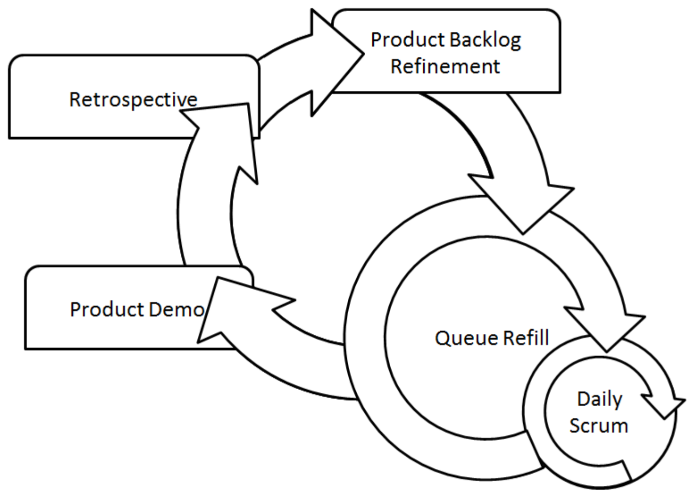


Figure 3. Sprint Cycle

At the beginning of each Sprint Cycle (see Figure 3), the team conducts the Product Backlog Refinement meeting. During this meeting, the team determines which tasks needed to be completed during the Sprint. Overall control of the task priorities are determined by the Product Owner. This phase determines the direction of the project and sets the goals for the Sprint, which is crucial for ensuring the customer gets what they want at the end of the project. Following the priorities set in the Product Backlog Refinement for the Sprint, a smaller group mainly consisting of the developers, the Project Manager, and the Scrum Master meets to determine the work for the next week in the Queue Refill meeting. The tasks come from the Product Backlog determined by the Product Owner. The developers, Project Manager, and Scrum Master gather each day for a Scrum. During this time, the team discusses what work was accomplished, what needs to be done, and any roadblocks preventing forward progress. The Scrum Master leads the discussion and takes action to remove any roadblocks preventing the team from moving forward. The developers then begin working the project tasks. Work continues in the cycle until near the end of the Sprint and the Product Demo. In this demonstration of the new software release, the Product Owner and all stakeholders are shown the new features or changes developed during the Sprint. The Demo is a key component of Agile in that stakeholders provide feedback on the new features and potentially make recommendations for other features. Ideas generated during the Demo are captured and added to the backlog for future consideration. Following the Product Demo, the Product Owner, Project Manager, developers, and Scrum Master complete a Retrospective to reflect on what went right/wrong during the last Sprint, identify key performers, and set the tone for the next Sprint. The Sprint Cycle is then complete but the project continues with the Product Backlog Refinement meeting to start the next Sprint. Work continues until the Product Owner and all Stakeholders are satisfied with the product.

## 4. OPERATIONAL IMPLEMENTATION

OVATION Prime 2013 was originally created as a science research tool as well as a forecast tool. To run in an operational environment, the original prototype code needed to be hardened and made more secure. Hardening ensures the model can handle live data, which can often be erroneous or push the limits of the mathematics in the algorithms. Hardening also ensures the model does not consume excessive resources in the shared operational environment. Operational centers are very concerned with security of the software running in these environments. Security analysis must be conducted on all software before deployment onto operations systems. Since the prototype code was delivered in a programming language that made it difficult to certify for the operational center, the prototype code was converted to a more suitable language. A theoretical basis document was also developed with the prototype to ease the conversion process. This fundamental decision allowed for a reverification of the algorithms in the model to ensure proper deployment of the science into the operational center during the conversion process.

## 5. LESSONS LEARNED

While the project was successful in delivering an improved capability to operations, there were still opportunities for improvement. The team documented lessons learned throughout the project and reviewed these lessons at completion. The most important lessons learned are described here.

Reach back to the prototype scientists is important. Entering into the project, the consensus was the model was scientifically sound and ready for conversion to operations with only a software porting required for success. During the conversion process, numerous software tests on each software component revealed some inconsistencies when compared to the theoretical basis document. Consultations with the APL scientists quickly helped resolve the issues and the code was corrected resulting in a more accurate code base for the operational model. These corrections were also fed back to the researcher's prototype. This ops-to-research (O2R) benefitted the research community as well. Access to the scientists at APL was a key element in the success of the overall research-to-operations (R2O) effort.

The System Engineers and Software Developers that work on the targeted infrastructure need to be involved in model development much earlier than the transition. Generally, scientists develop models. These prototype models have a significant dollar value that includes the labor and validation expenses. The general perception is that any changes to the baseline would invalidate the prototype rendering it less capable. However, these models are generally not capable of functioning in an operational environment and often suffer from pitfalls of overlooking good software engineering design. If the engineers and developers that maintain the operational infrastructure are involved in the early design decisions, the transition to operations will be much easier since less rework would be required for transition. Security issues can be avoided with proper software design practices. Targeted infrastructure interfaces can be built into the prototype. If these practices were put into place, there would be no need to revalidate the model after the research to operation effort.

Considering these two lessons, we envision a design concept that includes representatives from both science and information technology. Figure 5 shows the relative contribution of scientists and IT engineers over the course of product development. The technical readiness level (TRL) is a systematic evaluation used to describe the maturity of technology [18]. The TRL ranges from (1) Basic Technology Research to (9) Fully Operational. See Table A1 in Appendix A for definitions of each TRL.

At TRL 1, scientists perform the basic research to describe a physical process and begin to develop a prototype. From TRL 2–6, documentation of the scientific algorithms should be available (perhaps even in peer-reviewed literature) to hand off to information technology (IT) engineers. This handoff should include algorithm description documents for key algorithms and any prototype code. The IT systems and software engineers should be involved with some initial design decisions in the lower TRLs. At about TRL 6, a handover

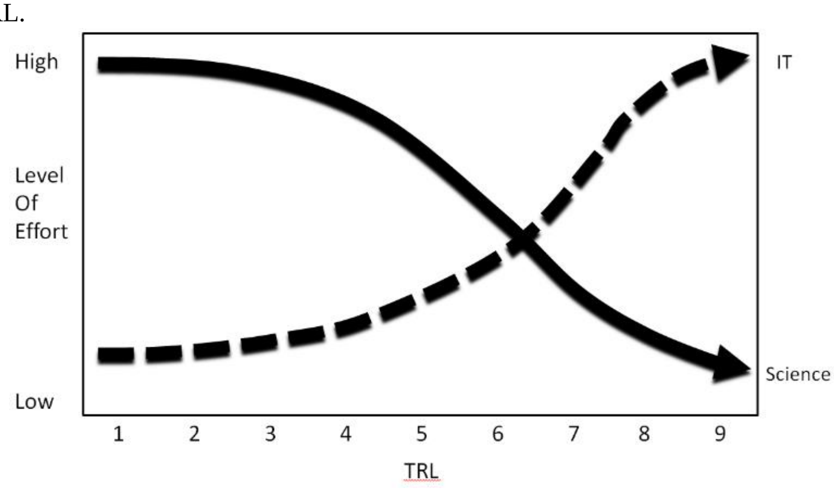


**Figure 4. Expertise Participation vs TRL**

takes place where now the IT engineers take over the project to optimize the code for operational infrastructure. Their goal is to meet stringent requirements for operational performance, security concerns, and integration into existing system components. The science team should remain involved to ensure integrity of the scientific results and scrutinize all changes. Otherwise, the IT engineers continue with their design and development. This method should ensure a very robust baseline that contains the best algorithms the science can offer.

## 6. SUMMARY AND CONCLUSIONS

This project delivered an improved capability to space operators. The OVATION Prime 2013 model produces output at a higher resolution and cadence than the previous auroral specification model in operations. It is reliable under a wider range of solar conditions and with the addition of the solar wind propagator and auroral boundary algorithm provides a more complete depiction of auroral characteristics. Another primary benefit is the improved latency over the charged particle driven models, which suffered from on-board storage and playback to ground receiver delays. Driven by solar wind, OVATION Prime produces a nowcast of a few tens of minutes versus an hour old specification. Agile processes and tools were used during the technology transition from research to operations and provided the flexibility to deliver a superior product. Stakeholders remained involved throughout the process and the Product Owner made all decisions on the direction of the project and its priorities. The experience of having Engineers, Software Developers, and Scientists all supporting OVATION Prime integration within a small team allowed us to deliver a high quality product. Transparency was a fundamental tenant of the team. Demonstration of capability every four weeks, weekly queue refill meetings, and daily scrums ensured that transparency. Agreement up front on the Definition of Done assured developers and the product owner both understood the nature of the project. When issues arose, the team prioritized the tasks to ensure requirements and the Definitions of Done were met.

## 7. ABBREVIATIONS AND ACRONYMS

ACC - Air Combat Command
ACE - Advanced Composition Explorer
AFW-WEBS - Air Force Weather Web Services
DoD - Department of Defense
DSCOVR - Deep Space Climate Observatory
GSE - Geocentric Solar Ecliptic
IT – Information Technology
IMF – Interplanetary Magnetic Field
Km/s – kilometers per second
MLT – Magnetic Local Time
NASA - National Aeronautics and Space Administration
NOAA - National Oceanic and Atmospheric Administration
NSWP - National Space Weather Program
O2R – Operations to Research
OVATION - Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting
R2O – Research to Operations
SATCOM - Satellite Communications
SMC - Space and Missile Systems Center
TRL – Technology Readiness Level
UHF - Ultra High Frequency (300 – 3000 MHz)
USAF - United States Air Force

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# 9. APPENDIX A

Table A1. Technical Readiness Level Definitions from [18]

| TRL | Definition | Description | Supporting Information |
|---|---|---|---|
| 1 | Basic principles observed and reported. | Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties. | Published research that identifies the principles that underlie this technology. References to who, where, when. |
| 2 | Technology concept and/or application formulated. | Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies. | Publications or other references that outline the application being considered and that provide analysis to support the concept. |
| 3 | Analytical and experimental critical function and/or characteristic proof of concept. | Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. | Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed. |
| 4 | Component and/or breadboard validation in a laboratory environment. | Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory. | System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals. |
| 5 | Component and/or breadboard validation in a relevant environment. | Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components. | Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals? |
| 6 | System/subsystem model or prototype demonstration in a relevant environment. | Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment. | Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level? |
| 7 | System prototype demonstration in an operational environment. | Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space). | Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level? |
| 8 | Actual system completed and qualified through test and demonstration. | Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications. | Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design? |
| 9 | Actual system proven through successful mission operations. | Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions. | OT&E reports. |