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AN INDEPENDENT TECHNICAL REVIEW PROCESS FOR GOVERNMENT DEVELOPED MODELS: HASDM AS A CASE STUDY

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The Joint Astrodynamics Working Group (JAWG) was established by U.S. Space Command with the intention of overcoming the chasms between organizations that do Astrodynamics related research and development. In 2001, the JAWG sought to apply independent technical evaluations to new models prior to operational implementation. This process was applied to the Air Force Space Command implementation of the High Accuracy Satellite Drag Model (HASDM) to aid in the determination of atmospheric drag effects on low satellite orbits. The JAWG conducted an independent technical review of the HASDM theory, using many experts in the field. Lessons learned from the review process are captured and provide a foundation for developing a future process to implement and integrate new concepts into the operational military space architecture.

INTRODUCTION

Disclaimer: Many of the statements made in this paper are the opinion of the author. The author does not intend to speak on behalf of any organization. The comments are intended to initiate discussions to improve the way business has been done in the past. The material that is presented here is based on the author's personal experience while leading the JAWG and facilitating the HASDM Technical Review effort.

Historically, new astrodynamic models and techniques have been implemented in military systems without independent technical review. The primary reason was a perception of national security. Although well-intentioned, these attempts have been largely unsuccessful and have had several unintended negative consequences in the field of astrodynamics. These include a developing parochial mentality with regard to the general astrodynamic community. Other unintended consequences include the exclusion of most academic and research oriented representatives of the community from any and all applications having to do with operational astrodynamics.

The result is that innovations that have been investigated and proven over the course of many years by the academic community have not been implemented. The exception has been when these innovations were redeveloped by "trusted agents." However, innovations developed by "trusted agents" have not been verified for correct implementation through an independent review process. This has further added to the rift between the operational and research astrodynamics communities.

Forums such as the Joint Astrodynamics Working Group (JAWG) were established by U.S. Space Command in the late 1990's with the intention of overcoming many of these chasms between organizations. Leadership of the JAWG was initially a joint venture of the U.S. Space Command Space Operations (J3) and Analysis (AN) directorates. Later, the leadership was transferred solely to AN.

As part of the JAWG charter, the organization embarked on an ambitious plan to apply independent technical evaluations to new models prior to their operational implementation. The first and only opportunity to employ the process was when Air Force Space Command accelerated the implementation of their High Accuracy Satellite Drag Model (HASDM) to aid in the determination of atmospheric drag effects on low satellite orbits. This is a particularly useful example as several other organizations and researchers were exploring the general notion of Dynamic Calibration of the Atmosphere (DCA), and had already invested significant time and resources to solving the problem. In fact, several solutions were available to the Air Force before the HASDM effort even began. To accommodate this accelerated schedule, the JAWG conducted an independent technical review of the HASDM theory, using many of the experts in the field.

This paper captures the lessons learned from the review process as it was applied to the HASDM. The review process and the lessons learned should provide a foundation for developing a future process to implement and integrate new concepts into the operational architecture for the military. Since U.S. Space command and the JAWG no longer exist, the responsibility will need to be assigned to a new organization with oversight authority.

JOINT ASTRODYNAMICS WORKING GROUP

The JAWG was originally established by the J3 as a sub-committee of the Space Surveillance Working Group (SSWG). The leadership was shared between the J3 representative and the AN representative. In 2000, AN was designated as the sole leadership of the JAWG and the organization was formally elevated in status to be its own working group and not a sub-group of the SSWG. Membership was open to SSWG members who had an interest in participating in coordinating astrodynamic work among military organizations. Representation included Air Force, Navy, Army, NASA, NRO, and various contractors and technical experts.

The JAWG's purpose was to coordinate astrodynamics research, development, testing, evaluation, and implementation to accomplish the space surveillance mission. This responsibility included trying to reconcile the decades long stove-piped development efforts of the differing services, establishing unified level astrodynamic/space surveillance standards, promoting cooperation between participants, and ensuring compatibility and interoperability between the services while ensuring customer needs were being met.

HIGH ACCURACY SATELLITE DRAG MODEL

The concept of dynamically calibrating the atmosphere (DCA) is not a new one. Documented work in the United States and Europe was occurring all through the 1990's. As early as 1991, Nouel et al used observed drag effects on SPOT 2 to improve the orbit precision of ERS1 [1]. Although Nazarenko began working the issue in the 1980's [19], he specifically introduced the U.S. Space Surveillance Community to his work of dynamically calibrating the atmosphere for space surveillance applications at the U.S.-Russian Space Surveillance Workshop in 1996 [2, 3]. Following this forum, the C.S. Draper Laboratory sponsored small study contracts to improve the visibility of Russian developed techniques in the United States, including the Russian DCA solution. In 1997, Marcos et al investigated using 1 LEO satellite to improve the drag modeling of 3 other LEO satellites [4]. This effort evolved into Modified Atmospheric Density Model (MADM) [5] which then evolved into HASDM [6]. Other efforts included the Naval Research Labs' (NRL) investigation of using Special Sensor Ultraviolet Limb Imager (SSULI) data to determine corrections to the MSIS atmospheric density model [7] and Storz's investigation of estimating density corrections from energy dissipation rates (EDR) [8]. Both efforts were incorporated into the HASDM effort as comparison data [6, 9]. Unfortunately, SSULI data was not available at the time and the EDR method was not sufficiently independent to validate the method.

HASDM was a project of the AFSPC/SWC Space Battlelab and is also the name of a collection of model improvements proposed by the Space Battlelab HASDM team. The Space Battlelab sponsored the demonstration and development of a new drag model to improve Space Object Catalog maintenance using the more precise special perturbations techniques. There are two components of the HASDM project: a dynamic calibration of the atmosphere (DCA) technique featuring calibration adjustments to the exospheric and inflection point temperatures within the Jacchia 1970 atmospheric density model [10] and the development of a new solar flux proxy, E10.7, that depended on the detection of EUV energy [11]. The technical details of both portions of the project are extensive; therefore the theory itself is not presented in this document. For background information on the HASDM technology, consult the *Proceedings of the AIAA/AAS Astrodynamics Specialist Conference*, Monterey, CA, 5-8 August 2002 which held a special session on HASDM [6, 9, 10, 11, 12].

While the actual Space Battlelab project has ended, the core of the HASDM development team continues to receive funding to operationalize the HASDM project. These follow-on projects are still referred to within the space surveillance community under the name HASDM.

TECHNICAL REVIEW PROCESS

On August 27, 2002, the Joint Astrodynamics Working Group (JAWG) under the leadership of the H.Q. U.S. Space Command (USSPACECOM) Analysis Directorate (AN) hosted a Technical Peer Review meeting to review the High Accuracy Satellite Drag Model (HASDM). The meeting consisted of one day of briefings and question and answer sessions (Q&A), allowing the research and development community the opportunity to critically evaluate the HASDM project. Following the meeting, additional written feedback was provided by the reviewers.

Invitations were issued to the JAWG, Space Surveillance Working Group (SSWG), HASDM team, and American Institute of Aeronautics and Astronautics (AIAA) Space Flight Mechanics mailing lists. Invitations were also posted at the August 2002 AIAA/AAS Astrodynamics Specialists Meeting and sent to other industry and academic experts on a one by one basis. The invitations suggested passing along the information to an even wider distribution of people. The meeting attendees included industry experts in the areas of estimation, space surveillance, orbital dynamics, and atmospheric physics. Representatives of AFSPC, NAVSPACE, NRL, USSPACECOM, NASA (MSFC, JSC, JPL), NRO, and other organizations from academia and industry were in attendance. Total attendance at the review meeting included 70 people who attended in person and several others that participated via audio telecon. People in attendance included experts in estimation theory, space surveillance, orbit determination, atmospheric density modeling, and atmospheric physics.

The Technical Peer Review addressed both the DCA and the E10.7 developmental projects within HASDM. The intention of the review was to examine the assumptions, methods, tests, results, and conclusions of the Space Battlelab project and provide insight to decision makers before the project would be transitioned to later stages of development. An after review report summarized the comments, opinions, and recommendations about the HASDM project up through the date of the Technical Peer Review. Because U.S. Space Command merged with U.S. Strategic Command and all Review associated personnel were no longer associated with the Review, the after review report was never officially released. However, the draft report was distributed to all participants including to representatives' chains of command.

AN considered inputs from the individual reviewers when compiling its portion of the report. Individual inputs were solicited via survey response (see Appendix) and were then filtered in order to remove organizational biases, inaccuracies, technical concerns that were merely due to lack of awareness of previously presented material, and finally distilled in order to remove obvious attribution. AN as the intermediary and review leadership established itself as being centrally responsible for all criticism.

The HASDM project is a dynamic research and developmental effort that has been moving ahead at a rapid pace. Therefore, evaluating the project required examining it at a snapshot in time. The report addressed the project as it had been presented prior to the Technical Peer Review and at the Technical Peer Review. Some of the matters that had been documented in the report may have been addressed during the period of time between the Review and the completion of the report or may have been addressed in subsequent test and development periods since then.

Review Outcome

Before proceeding, it is important to realize that many of the comments submitted after the meeting were favorable toward the project, but did not include substantial elaboration. Detailed review comments, by nature, tend to be critical and thus most of the detailed comments highlighted the negatives of the project over the positives. Many of the positive comments referred to the initial improved results of the project and the hard work that the HASDM team put into the project. One other caution is that the operational space surveillance community was, and still is, highly politicized with substantial polarity between sub-groups. This is largely due to the funding which has historically favored certain personalities in proximity to the government astrodynamics community.

Representatives of the core JAWG constituency provided comments on the project. Individual feedback was included within the draft AN report. As a demonstration and example of the nature of Review feedback, below is the summary of this feedback. This feedback was delivered to AN in the form of official memoranda, often from superiors in the representatives' chains of command:

- H.Q. U.S. Space Command (USSPACECOM) Analysis Directorate (AN) as Chair of the JAWG had determined that the DCA portion of the project had merit, but that there were gaps in the work that needed to be addressed in later stages of development. The E10.7 portion of the project did not have demonstrable benefit at the time and should return to a research and development phase. Additionally, AN cited instances where conclusions could not necessarily be drawn from the presented results. The AN report also included inputs from individual reviewers.

- The USSPACECOM Operations Directorate (J33) representative to the JAWG agreed that the DCA portion of the project had merit, but the apparent improvement under ideal conditions was significantly less than expected. J33 also agreed that the E10.7 portion of the project was not ready to proceed to the next stage of testing [13].

- The Air Force Space Command (AFSPC) Space Surveillance Network Operations Branch (DOYS) representative to the JAWG was convinced that HASDM had merit and operational implementation should be pursued in order to support the operational users who had expressed interest in having HASDM implemented as soon as possible. AFSPC was already pursuing operational testing [14].

- The Naval Network and Space Operations Command (NNSOC) Operations Division representative to the JAWG was of the opinion that the HASDM results to date were sufficiently interesting to warrant further investigation, but that it was premature to consider implementing HASDM for space control operations. NNSOC also had reservations regarding several technical aspects of the DCA portion of the project and recommended that the E10.7 portion of the project be returned to a research and development phase [15].

- The U.S. Army Space Command (ARSPACE) representative to the JAWG recommended that HASDM be operationally implemented. However, ARSPACE also recommended that HASDM undergo cost versus benefit testing and be evaluated against other candidates to adequately confirm success criteria [16].

- The NASA Johnson Space Center (JSC) representative to the JAWG was confident that implementation of the DCA would provide improvements toward meeting the USSTRATCOM Capstone Requirements Document. JSC would have liked HASDM to progress to operational use as expeditiously as possible [17].

- The National Reconnaissance Office (NRO) representative to the JAWG had followed the HASDM project and stated that HASDM would provide tangible improvements to the flight safety of National space programs. NRO recommended implementation of the DCA immediately after satisfactory completion of the scheduled operational testing [18].

Detailed evaluation of HASDM began with looking at the selection of the specific DCA method. Criticism focused on the selection of the Air Force proposed solution without assessing alternative techniques.

The testing procedures were examined in detail with criticism focusing on issues of independence of calibration and evaluation sets as well as lack of specified evaluation criteria. The tests included comparisons of results between ‘evaluation’ and ‘calibration’ sets, ballistic coefficient variability, epoch accuracy versus prediction accuracy, covariance realism, performance of E10.7 vs. F10.7, evaluation of an alternative formulation of the same DCA model, and how sensor tasking was affected. The specific findings are being left out here because the project has obviously moved on since the Review.

Development of the HASDM theory was a focus of investigation. This included examining the required data distribution, the estimation of biases, and issues of parameterization and observability for the DCA portion. For the atmospheric modeling, issues of base density model and atmospheric physics were analyzed.

LESSONS LEARNED

Technical Review Material

It is important to note that AN did not seek the end of the HASDM theory development. On the contrary, the HASDM project represented one of the biggest leaps forward in drag modeling in several decades and AN encouraged further research and development efforts. However, there were efforts being taken within the operational community to implement HASDM in the catalog maintenance operational system. The issue for AN and the JAWG was whether or not HASDM was ready to move on to the next stage toward operational implementation. With this and the previous comments in mind, AN made the following recommendations that can be applied to future model development efforts:

Specific criteria need to be established that allows for objective evaluations of any new model between each stage of progression toward implementation. This criteria needs to consider differences between calibration and evaluation satellites, typical and special tasking, and conducting separate tests for disconnected models (like DCA vs E10.7) so that each model’s impacts may be assessed. The two HASDM components should not have been considered simultaneously.

Several opportunities for analysis of alternatives were encountered during the HASDM program. Any model development should consider these analyses in the course of development:

- Selecting model revision approaches (this would have substantiated claim that HASDM DCA was the best approach)
- Selecting baseline models
- Selecting parameterizations that maximize observability
- Selecting auto-regressive techniques to improve estimate persistence
- Selecting organizations to provide independent technical validation and verification of results

The tests conducted for the HASDM project suffered from a lack of independence. AN recommended that tests to meaningfully evaluate the HASDM performance should include comparisons to externally provided precise ephemerides. For future model reviews, if objects tracked by SLR or GPS are not available, then objects with proprietary orbits or AFSCN derived orbits should be used to test for epoch solution improvement. When possible, software that uses other methods than those used for the experiments should be employed for determining reference orbits to increase independence of algorithms and models.

The test results presented at the review were insufficient for determining the success of HASDM. AN recommended the following tests should be performed and the results evaluated versus established criteria:

- Sensitivity tests showing how the results would vary due to changes to models and inputs
- Estimation/Prediction results of separate models tested separately
- Estimation/Prediction statistics of only the evaluation set of satellites
- Test covariance realism without applying alternative corrections such as consider parameters to either the “truth” or the test runs

To aid decisions about operational implementation, the following tests of operational suitability are required:

- Computational load on operational system to compute additional corrections
- Computational load on operational system to use additional corrections
- Computational load on operational system for producing extrapolated backwards-compatible solutions

- Accuracy of extrapolated backwards-compatible solutions
- Interoperability with other owner operator systems

Technical Review Process

The Review process as a first of its kind opportunity had some flaws that could be resolved in future attempts at review. Because of the significant amount of material and the large attendance at the review (both in person and via telecon), the meeting structure lacked sufficient time for questions and answers. AN attempted to resolve the issue in the weeks before the review by soliciting questions in advance and resolving them via e-mail. The goal was to have the attendees understand the model and its development prior to the Review so that the review would not be hampered by basic questions of physics or math. The HASDM team responses to these questions were distributed to the entire list of confirmed attendees prior to the meeting. Despite this, considerable time was spent in answering questions due to lack of reviewer preparation. A two day meeting would have been useful, but it would have been more difficult to have all the attendees adjust their schedules to accommodate.

The other lesson learned was that because of the lack of formalization in the process, there were no mechanisms established for tracking the resolution of criticisms raised from the Review process. AFSPC/DR attempted to incorporate some of the Review results in their processes of HASDM, but were hampered by the loss of access to the Review leadership when U.S. Space Command disappeared. In the future if there is a formalized process, the process can persist beyond the life and death of organizational entities.

RECOMMENDATIONS

HASDM Recommendations

Before the final decision to implement the HASDM theories was made, a cost/benefit analysis should have been conducted. Marginal improvement at substantial cost might not be in the best interests of the operational users. If the cost/benefit analysis showed that implementing the HASDM theories was not advisable at the time, work could have continued to improve the model and have implementation be reconsidered later.

It has been pointed out that the two principle customers, NRO and NASA, would have preferred to implement the HASDM theories even if the improvement was only marginal. It may have been reasonable for them to sponsor an off-line system to assist the maturation of the theories. This would have provided the NRO and NASA with access to the HASDM derived catalog with minimal effects on the operational system.

Whether the E10.7 proxy eventually holds promise at improving the drag modeling, it was not yet ready for operationalizing. AN recommended that research continue with the E10.7 parameter if a sponsor steps forward, but implementation and efforts toward implementation needed to be put on hold until the benefit of the parameter could be demonstrated according to specific criteria. AN also recommended an analysis of alternatives to determine whether a new daily E10.7 parameter is the best way to proceed versus creating a density model that uses the E10.7 source data directly as inputs.

The data used for the HASDM project, including the reference orbits, the SSN data, and the DCA estimated parameters should be distributed to the researchers in the community so that they can investigate those options that the HASDM team had insufficient time to address and to push the theories further. Ultimately, the DCA solutions might serve as inputs in refining a more physically meaningful density model.

The HASDM follow-on activities had already been planned and many had been funded. Full catalog testing occured in the Fall of 2002 as part of the Space Situational Awareness Command and Control (SSA C2) efforts, and testing in the operational environment was scheduled for the late winter/early spring. Expected implementation by the proponents of HASDM was the following fall. Before moving HASDM into the operational system, a cost-benefit analysis needs to be conducted that considers all potential consequences to the operational system and its users. To the best of the author's knowledge, this has not yet been done.

The consequences of including the HASDM techniques in the operational systems include:

- Processing overhead for computing DCA corrections must be evaluated.
- Processing overhead for using the computed DCA corrections must be evaluated.
- Communications issues between producers and users must be resolved. This includes resolving "extrapolation differential correction" issues of time and effectiveness. This also includes determining what information needs to be transmitted to the users to effectively use the product and how to communicate that information.
- Operational impacts of including HASDM as part of the AFSPC Astro Standards must be resolved.
- Delivery of E10.7 parameters to operation producers (and potentially users) must be indefinitely funded.
- Impact to the Alternate Space Control Center and its users must be determined.
- CONOPS must be developed.

- NASA must re-determine the scale factors on the covariance.
- The consider parameter must be re-determined.

Finally, how can others (industry and academia) gain access to the model and the data in order to investigate how best to integrate HASDM into their systems and how best to contribute by advancing the science? To this day it is still difficult – if not impossible – to obtain the actual observational and positional data in order to conduct an independent analysis to provide confirmation and verification of HASDM claims.

Technical Review Recommendations

This process of Technical Review should be applied to any new model or significant modification prior to being implemented in an operational system. An organization needs to come forward with the responsibility to organize and oversee Technical reviews of proposed new models. This organization needs the authority to enforce the process, the independence to give the process credibility in the eyes of the scientific community, and the impartiality to avoid corrupting the process with preconceived biases. The Department of Defense needs to embrace and formalize this process so that the Technical Review becomes a requirement for operational implementation. This process needs to go beyond the review stage and include mechanisms for tracking the resolution of any and all criticisms raised during the review process.

SUMMARY AND CONCLUSION

This paper has summarized a Technical Review process that was implemented in the review of the HASDM. The Review process identified criticisms of execution in the model development and highlighted areas of concern, but more importantly, the process serves as an example and a prototype for conducting future reviews along these lines. The most important conclusion to be drawn from this paper is that technical review is necessary in order to gain community buy-in as well as identify loose ends that need to be secured prior to implementation. In order for this to happen, data and technical information must be made available to industry and academia. Resolution of this issue is wrapped up in the upcoming Security Classification Guide (SCG) for Space Control data. However, once the SCG is published, there will still need to be a concerted effort to overcome institutional inertia that may obstruct the release of data to foster teamwork and enhance cooperation and interoperability.

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APPENDIX

HASDM Technical Review After Meeting Survey

Thank you for supporting the HASDM Technical Review. Now that you have seen the briefings and participated in the question and answer session, we at U.S. Space Command would like for you to contribute closing opinions. The following survey will address both the HASDM project and the Technical Review process. Please complete this questionnaire now and turn it in before leaving or, alternatively, you may take it with you and e-mail your responses to Dr. Michael Gabor at mike.gabor@peterson.af.mil by Friday, 6 September 2002. Feel free to use the backside of the survey to continue your responses.

Part I. Respondent Information

Name:

Organization representing:

Contact Information:

Experience relevant to this Technical Review:

Part II. HASDM Project (please comment on the DCA and/or the inclusion of the E10.7 parameter as you feel appropriate)

1. Are the assumptions used to develop the HASDM project complete, adequate, and consistent with observed physical phenomena?

2. Are the HASDM methods consistent with the assumptions, the source data, and the laws of physics and commonly accepted practices of mathematics?

3. Are the tests performed by the HASDM team consistent with the theories that were developed, do they adequately provide a measure of the capabilities, and do they provide an independent assessment of the capabilities?

4. Are the results from the HASDM testing meaningful?

5. Are the conclusions from the HASDM project traceable to the results of the tests?

6. Please provide additional thoughts and opinions on the HASDM project.

Part III. HASDM Technical Review

1. Did this meeting succeed in providing a Technical Peer Review of the HASDM project?

2. What were your expectations of the review process prior to attending the HASDM Technical Review?

3. How did the review process (including this meeting) differ from those expectations?

4. Is this process valuable and effective?

5. What would you recommend to increase the value and effectiveness of this process if it is used for evaluating other projects in the future?

6. Please provide additional thoughts and opinions on the Technical Review process.