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# AN OVERVIEW OF THE NEXT-GENERATION NATO REFERENCE MOBILITY MODEL (NG-NRMM) COOPERATIVE DEMONSTRATION OF TECHNOLOGY (CDT)

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**ABSTRACT**

*The NATO Reference Mobility Model (NRMM) is a simulation tool aimed at predicting the capability of a vehicle to move over specified terrains. NRMM was developed and validated by the U.S. Army in the 1960s and '70s, and has been revised and updated through the years. Although NRMM has proven to be of great practical utility to the NATO forces, it exhibits several inherent limitations when compared to modern modeling tools. A NATO Research Task Group (RTG) committee was formed to develop a Next-Generation NATO Reference Mobility Model (NG-NRMM). In September 2018, a 3-day NATO Cooperative Demonstration of Technology (CDT) event took place at the Michigan Technical University / Keweenaw Research Center (MTU/KRC) in Northern Michigan to showcase the committee's work and the key differences between legacy and next generation mobility prediction software. This paper summarizes the CDT event and actions performed, describes the value added, identifies gaps, and outlines a path forward to address many of those gaps now that the four year effort has concluded.*

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## 1. INTRODUCTION

The NATO Reference Mobility Model (NRMM) is a simulation tool aimed at predicting the capability of a vehicle to move over specified terrains. NRMM was developed and validated by the U.S. Army in the 1960s and '70s, and has been revised and updated through the years. NRMM is traditionally used to facilitate comparisons between vehicle design candidates and to assess the mobility of existing vehicles under specific scenarios. Although NRMM has proven to be of great practical utility to the NATO forces, it exhibits several inherent limitations when compared to modern modeling tools. It is based on empirical observations, and therefore extrapolation outside of test conditions is difficult or impossible, and it is heavily dependent on in-situ soil measurements. Only two-dimensional analysis is possible; lateral vehicle dynamics are not considered, and it does not account for vehicle dynamic effects, but instead only considers steady-state conditions. It is specific to wheeled/tracked vehicles and is not easily implementable within modern vehicle dynamics simulations.

To remedy these problems a NATO (North Atlantic Treaty Organization) Research Task Group (RTG) committee, AVT-248, was formed, which consisted of 70 members from 15 nations, and ran from 2014 to December 2018 to develop a Next-Generation NATO Reference Mobility Model (NG-NRMM) [1]. In September 2018, a 3-day NATO Cooperative Demonstration of Technology (CDT) event took place at the Michigan Technical University / Keweenaw Research Center (MTU/KRC) in Northern Michigan to showcase the work of AVT-248 and the key differences between legacy and next generation mobility prediction software. The CDT event provided a forum for contributing committee members and software developers to highlight a prototype process that showcased the state-of-the-art in mobility prediction and simulation technologies through a loosely integrated set of methodologies and tools.

This paper summarizes the CDT event and actions performed, describes the value added, identifies gaps, and outlines a path forward to address many of those gaps now that the four year event has concluded.

## 2. Objectives

The objective of the CDT was to demonstrate the most advanced capabilities in ground vehicle modeling and simulation, with a particular focus on mobility over soft and marginal terrains, typical of ground combat operations. The CDT included technical sessions on simple and complex terramechanics, demonstrations of field soil sampling in relevant soil types, vehicle mobility displays, and simulations using a high mobility platform on representative terrain and soil. The CDT was structured to demonstrate the capabilities of NG-NRMM in six scientific thrust areas:

- Thrust 1 - Geographic Information System (GIS) - Terrain and Mobility Mapping: Identify a GIS-based mapping tool that implements and integrates existing, valid mobility metrics (%No-Go and Speed-Made-Good) in an open architected environment
- Thrust 2 - Simple Terramechanics (ST): Identify the most promising existing parametric terramechanics models able to meet NG-NRMM requirements that provide a means of correlating terrain characteristics to remotely sensed GIS data
- Thrust 3 - Complex Terramechanics (CT): Identify the most promising existing physics based terramechanics models able to meet NG-NRMM requirements that overcome the limitations of parametric models
- Thrust 5 - Uncertainty Treatment: Identify the practical steps required to embed stochastic characteristics of vehicle and terrain data to enable probabilistic assessment of current deterministic mobility metrics (%Go/NoGo)
- Thrust 6 - Verification and Validation (V&V): Establish near-term vehicle-terrain interaction benchmarks for verification of candidate NG-NRMM M&S software solutions and lay the groundwork for long term validation data through cooperative development with test organizations and standards committees
- Thrust 7 - Data Gaps and Operational Readiness: Refine the operational requirements of NG-NRMM and identify gaps

*(Please refer to [1] for detailed explanations of each technology area)*

To be clear, NG-NRMM will not be a specific computer code but a set of NATO standards and benchmarks spelled out in a STANREC. A STANREC (STANdardizationRECommendation) is a NATO standardization document defining processes, procedures, terms, and conditions for common military technical procedures or equipment between the member countries of the alliance. It’s a non-binding document employed on a voluntary basis and does not require commitment of the Nations to implement the standards listed therein. A NG-NRMM NATO Standards STANREC, AMSP-06, ver1 Standards Document: “Guidance for M&S Standards Applicable to the Development of Next Generation NATO Reference Mobility Model (NG-NRMM)”, Allied Modeling and Simulation Publication-06 (AMSP-06, ver1), assigned by and coordinated with the NATO Modeling and Simulation Group (NMSG), is being developed. The AVT-327 Research Task Group (RTG) will establish the enduring process for development and configuration management of AMSP-06. The objectives and scope will be defined as a land vehicle mobility M&S open architectural specification that:

- is applicable to all land vehicle geometric scales
- implements GIS-based M&S methods and mobility metrics
- promotes tool modularity, interoperability and portability
- embraces scalable M&S at multiple levels of resolution
- includes M&S verification and validation maturity scales and practical benchmarks
- includes standards and databases for terramechanics experimental data measurement methods that support the terramechanics models

The STANREC guidance codifies results of the NG-NRMM effort and establishes an enduring artifact. It establishes a baseline as well as a development path for NATO nation mobility modelling methods, benchmarks, and a soils database that should be applied to all physics based simulations of operational land and amphibious mobility among the alliance.

## 3. Summary of Actions Performed

The CDT was divided into four (4) phases; PHASE 1 - Collect vehicle test data to calibrate computer-based models, PHASE 2 - Mobility Simulation and Analysis, PHASE 3 - Model Comparison to Live Test Results, and PHASE 4 - the Cooperative Demonstration of Technology (CDT) event. The Fuel Efficiency Demonstrator Alpha (FED-Alpha) shown in Figure 1 was designated as the test vehicle for the CDT and was ideal for NG-NRMM purposes as it had considerable design and technical data available, as well as partially validated models for dynamic and powertrain performance.

**Figure 1.** FED-Alpha Vehicle. Graphic & Hardware

The FED-Alpha [2] was designed to be a high-mobility, highly-capable and survivable four passenger tactical vehicle that would maximize fuel efficiency across all vehicle systems. It was selected for this evaluation due to its relevant physical characteristics and performance, which are similar to those of the High-mobility Multipurpose Wheeled Vehicle (HMMWV), without the data sensitivity of a fielded system. Commercial software vendors as well as other interested developers were invited to participate in the AVT-248 committee activities and, subsequently, in the CDT event to gauge their software’s effectiveness and accuracy in modeling and simulating vehicles in off-road and soft soil environments. The software developers were tasked with modeling the FED-Alpha using their respective M&S codes and GVSC with using the legacy NRMM as a baseline simulation analysis for comparison purposes.

3.1 Phase 1-Test Data Collection: Field tests [3] were conducted by MTU/KRC to evaluate the automotive performance and mobility of the FED-Alpha vehicle and collect instrumented test data for model calibration and validation. MTU/KRC conducted the specified test events and measured and recorded both terrain data (simulation model inputs) and vehicle performance data (simulation model outputs). Table 1 presents a summary of the tests that were conducted and the corresponding simulation outputs that were collected and evaluated. The vehicle performance data was split into a calibration data set and a live test results data set.

| Test Name | Soil | Simulation Outputs |
|---|---|---|
| StraightLine Acceleration **(TOP 2-2-602)** | Pavement | Position, speed, acceleration histories |
| Wall to Wall Turn Circle Radius | Pavement | Max diameter of tightest circle position, speed, clockwise and ccw |
| Steady state cornering (30 m radius) **(SAE J2181)** | Pavement | Understeer/oversteer characteristics, steering angle, max. speed, lateral acceleration |
| NATO Double lane change **(AVTP 03-160 W)** | Pavement | Speed, path, steering angle, lateral acceleration, yaw rate, roll angle |
| NATO Double lane change | Gravel | Speed, path, steering angle, lateral accel, yaw rate, roll angle |
| Side slope with obstacle avoidance steer **(TOP 2-2-610)** | Hard-packed crushed mine rock | Side slope, speed, pass/fail |
| 60% Longitud grade | Pavement | Speed, grade, pass/fail |
| 0 to 30% Longitud grade | Coarse grain sand | Max grade at set speed, pass/fail |
| 4 inch half-round **(TOP 2-2-611)** | Pavement | Speed when 2.5g vert acc at driver's pos |
| 8 inch half-round | Pavement | Speed when 2.5g vert acc at driver's position |
| 10 inch half-round | Pavement | Speed when 2.5g vert acc at driver's position |
| 12 inch half-round | Pavement | Speed when 2.5g vert acc at driver's position |
| 18 inch vertical step | Concrete | Go/no-go and identify any interference |
| 24 inch vertical step | Concrete | Go/no-go and identify any interference |
| V-ditch | Concrete | Go/no-go and identify any interference |
| Drawbar Pull **(TOP 2-2-604)** | Fine Grain Organic/ Silty Sand - Wet | Drawbar pull vs. slip |
| Drawbar Pull | Fine Grain Organic/ Silty Sand - Dry | Drawbar pull vs. slip |
| Drawbar Pull | Coarse Grain Sand - Dry | Drawbar pull vs. slip |
| Asymmetric 1-1.5 inch RMS | Hard-packed crushed mine rock | 6-Watt absorbed power speed |
| Asymmetric 1.5-2 inch RMS | Hard-packed | 6-Watt absorbed power speed |
| Symmetric 1 inch RMS | Hard-packed | 6-Watt absorbed power speed |
| Symmetric 1.5 inch RMS | Hard-packed | 6-Watt absorbed power speed |

| Test Name | Soil | Simulation Outputs |
|---|---|---|
| Symmetric 2 inch RMS | Hard-packed | 6-Watt absorbed power speed |
| Symmetric 3 inch RMS | Hard-packed | 6-Watt absorbed power speed |
| Symmetric 4 inch RMS | Hard-packed | 6-Watt absorbed power speed |
| Symmetric 5 inch RMS | Hard-packed | 6-Watt absorbed power speed |
| Mobility Traverse | Composite of Natural Terrain & Engrd Course | Varied including speed-made-good map |

**Table 1.** Model Simulation/Live Test Matrix
***Red indicates courses that NRMM could not model***

3.2 Phase 2-Model Development – the objective of PHASE 2 was to develop a NG-NRMM modeling process, and then create and calibrate simulation models of the test events. It consisted of simulating mobility testing and predicting performance of live testing. Each participant was required to:

- obtain vehicle, terrain, and test calibration data
- developed a 3D, high-resolution, physics-based computer FED-Alpha simulation model completing each test
- Simulate the model over the set of digital terrain courses analyzed simulated results (Figure 2 illustrates an example of a software developer's FED-Alpha conducting longitudinal grade tests)
- Calibrate the model to the calibration test data
- Predicted the performance of the FED-Alpha and report results

Software developers communicated and shared best practices, including terrain data file formats and test scenario modeling, in developing the NG-NRMM modeling processes.

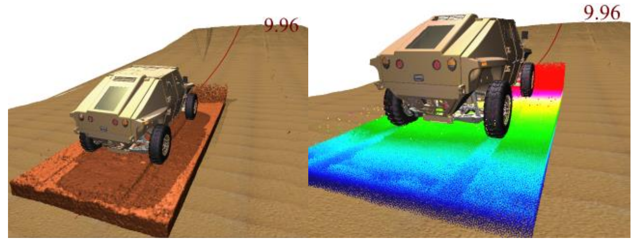


**Figure 2.** Example of simulations models

Software developers developed a Go/NoGo terrain map of the MTU/KRC terrain for the FED-Alpha vehicle and determined for each specified MTU/KRC unique terrain unit the maximum traversable speed in omni-directions. They also developed an Uncertainty Quantification (UQ) Map from the Go/NoGo Map developed in the prior task. This required an estimate of max speed for each terrain unit under the variation limits of the terrain. The range of speed estimates were computed into a probability, which was then mapped. Diverse and multiple solution methods, including ST and CT, were preferred and encouraged [4]. GVSC modeled and conducted the same analysis of the FED-Alpha using the current NRMM legacy code for comparison purposes.

3.3 PHASE 3-Model Comparison to Live Test Results: this phase consisted of comparing the PHASE 2 simulation results to live test results as illustrated in Figure 3, improving the PHASE 2 models, and quantifying model performance.


**Figure 3.** Model comparisons to live test results

Each participant compared the model results to the live test results for all tests conducted and, subsequently, verified model behavior and identified areas for model improvement, such as, more accurate mass and inertial properties, more accurate suspension stiffness and damping characteristics, and integration of improved bushing and tire models. Simulations were then re-run using improved model parameters, monitoring those parameters, and comparing improved model performance with live test data. Go/NoGo and Uncertainty Quantification Maps developed in PHASE 2 were also updated based on new information which allowed an updated comparison of the maximum speed made good for the traverse runs to the map results. Participants refined and reran their model(s) as necessary to quantify model mobility performance as accurately as possible. Partial results are in section four and full results are found in [5]

3.4 PHASE 4 – Cooperative Demonstration of Technology: The CDT was a three-day event held at the MTU/KRC test facility (Figure 4) with approximately 160 people attending each day. It was comprised of presentations and demonstrations of the latest technology developments in modeling and simulation of off-road mobility of ground vehicle systems and physical demos on the mobility traverse. The meeting was intended to be a critical peer review of the NG-NRMM AVT-248 and AVT-308 committee's NG-NRMM's effort(s).

**Figure 4.** NATO CDT event in Houghton, MI, USA

Attendees were introduced to NG-NRMM technologies through the following presentations:

- History, Motivation, and Goals for NG-NRMM
- NATO Task Group and CDT Objective
- NG-NRMM Virtual and Physical Demo Plan
- Geospatial Terrain and Mobility Mapping
- Simple Terramechanics Model & Data
- Complex Terramechanics Model & Data
- NG-NRMM Virtual Demonstration
- Uncertainty & Stochastic Mobility Maps
- NG-NRMM Verification and Validation
- NG-NRMM Standard
- Gaps and Operational Readiness
- CDT Results and Vision for the Future

*** Presentations located at* (ftp://ng-nrmm:thread$panel@nrmm.mtukrc.org)**

The NG-NRMM Virtual Demonstration was an "end-to-end software demo" that demonstrated how NG-NRMM adopted new technologies, modeling techniques, and computational tools to enable physics-based simulation of any vehicle design, in complex environments and scenarios. It described how an open and modular architecture was used to weave together CDT technologies to include GIS data inputs, terrain and soils data, the latest modeling and simulation technology, terramechanics, mobility event studies, uncertainty quantification, and mobility maps into an integrated set of tools and methodologies for mobility prediction that allows for incorporation of new methods as they become available. In addition, each participating software developer prepared suitable presentation materials for the event, which included live and/or recorded animations of the simulation events in the same orientation as videos of the live test events so that they could be compared and played in parallel. They also produced charts, explanatory materials and other artifacts relevant to demonstrate the quality of the work within the operational context of the NG-NRMM environment. The software developers presented the following talks:

- MSC - Military Vehicle Simulation with Adams: Mobility and Beyond
- CSIR - South African Mobility Prediction Software MOBSIM
- CML - Real-Time Vehicle Simulation using Vortex Studio
- VSDC - Wheeled Vehicle Mobility Prediction using NWVPM

- AU - ROAMS, a Fast Running Mobility Simulator Utilizing GeoTIFF Terrain Maps
- ASA - DIS/A Complex Terramechanics Software Tool for Predicting Vehicle Mobility

*** Presentations located* (ftp://ng-nrmm:thread$panel@nrmm.mtukrc.org)**

Participants were able to walk some of the courses and witness vehicle demonstrations of the vehicle traversing select terrains (RMS, soil pit, side slope, and sand grade courses) as seen in Figure 5.

**Figure 5.** NATO CDT vehicle/course demonstrations

## 4. Results/Lessons Learned

Although NRMM remains a useful tool for limited applications, the future of analytical soft soil mobility analysis rests with NG-NRMM. It holds the promise of allowing manufacturers, planners, and users the ability to model virtually any platform, over any soil and terrain type. The CDT has demonstrated that NG-NRMM can offer significantly better mobility and trafficability predictions although the CDT results are limited to the vehicles modeled and terrain traversed. Work is still required to demonstrate the accuracy of predictions over other vehicles, terrains, and soil types, which will still require investments in research and development to bring it to a fully mature state. The automotive test simulations highlighted the fact that NRMM lacks 3D dynamics capability and therefore only straight line tests could be simulated, whereas NG-NRMM based models were able to simulate all of the tests.

During the soft soil tests, drawbar pull (DBP) and variable sand slope (VSS), NRMM was only able to predict the DBP well in wet, fine grain soil and showed a large variation in VSS. It is well known that ST is challenged on sloped terrain, however, in the course of the CDT, predicting DBP and VSS in coarse grained sand also proved to be difficult. CT was better able to predict the VSS and the DBP results across all soil types, except dry course grain. Rut depth measurements were disturbed by flowing sand, and only a few developers were tracking multi-pass effects. Again, NG-NRMM predicted all soft soil events (with validation possible), except the coarse grain dry.

On the mobility traverse, NRMM greatly over-predicted the average speed compared to tests, whereas NG-NRMM was within 25% of the test speed in more than 75% of the traverse segments. It should be mentioned that NG-NRMM driver models do not have the same perceived speed limits as an actual test driver and will inherently drive faster than drivers may feel comfortable. Without question, NG-NRMM simulations were demonstrated to be in better test agreement with test results than NRMM.

## 5. Capability Gaps and Challenges

The gaps and challenges identified by the committee members fell into three categories; input, modeling, and output.

Modeling input gaps were data availability (especially soil), resolution, lack of a long term configuration management approach to a soil and terrain database, and advancement of the vehicle as a sensor method. Other input issues were with obtaining vehicle data, especially with increasing vehicle complexity, storing data with implications for adaptability and interoperability, and data security with increased complexity for data handling. Legacy terrain data also presents challenges such as: how to enhance obstacle representations, data gaps and how to generate additional soil parameters, and data that changes over time, which impacts the ability to update and subsequently use legacy data. Data confidence is another area where NG-NRMM will need improved methods for capturing data quality and confidence.

Terramechanics modeling was the second area where gaps/challenges were identified: moisture and vegetation effects, temperature and seasonality effects, vehicle-soil slip-sinkage parameter quantification methods, addressing bulldozing phenomena, experimental methods that address soil layer and load rate effects, and leveraging CT developments to extend the ST database. The ability to validate and calibrate high-fidelity finite element tire – soil models (Discrete Element Method) would be a more cost effective path forward for better modeling of the deformable tire and soil interface. Standardization across industries and solution providers is also critical. To date, advancements in NG-NRMM solutions (the use of multi-body physics, ST and CT and other tools) has been slowed by the lack of a unifying standard to govern their development and implementation. A single solution is not required, but a single, unifying standard that ensures optimal interchange of data and incorporation of new knowledge is.

Output was identified as the third area with model validation and verification as the biggest challenge. A benchmarking verification and validation plan will be necessary to assess potential NG-NRMM modeling methodologies, capabilities, and component models for vehicle dynamics, off-road mobility, intelligent vehicle operation, and geospatial data use and mapping, which will need to be included in the set of standards to guide the implementation of NG-NRMM, as well as its use and management. There is also concern that developing NG-NRMM for legged and small vehicles may not be viable in the near term as well as the capability to model and simulate performance in/around water, ingress and egress, obstacles, and vegetation. NG-NRMM is well suited for a wider exploitation and will provide a revolutionary step-up in mobility performance analysis capability. The challenge will be to understand how to carry that improvement forward, e.g., to logistic and combat simulations, since NG-NRMM alone does not address the 'so what' of improved discrimination between vehicles.

## 6. Recommendations / Way Forward to Tackle Remaining Gaps

Based on CDT results, it is clear that the need for continued investment in NG-NRMM is both warranted and required. These investments need to be focused in several directions:

- the generation of relevant soil and terrain datasets using remote sensing such as GIS to obtain soil properties, moisture, resolution, data size
- understanding how legacy datasets may be leveraged for application in today's physics based mobility modeling and assessment methodologies
- understanding, interpreting and correlating disparate data sources, such as cone index, bevameter, remote sensed topography, moisture content, historical land use etc.
- uncertainty quantification, which will require a better understanding of both the probability distribution of key parameters, and the sensitivity of soft soil mobility prediction results.

CDT software developers will need to demonstrate their capabilities while moving towards NG-NRMM compliance including multi-pass effects in ST models and the use of GIS to define terrains/soils. CDT terrain and soil data have been released, and a new STANREC RTG (AVT-327) will take up the development of a recommendation on the local high resolution format (such as TIN) for terrain in addition to the more global data format that is available as postings on a grid. CDT benchmark data sets are available and formally packaged to include vehicle, terrain, event descriptions and soil data used for each benchmark. There will also be established a DATABASE of Terramechanics soil properties and a CATALOG of global terrain data sets which will include the Monterey data set used in AVT-248 and the CDT data set when released. Challenges remain with uncertainty quantification such as how to develop variance data for each model type. Wheel based sensors provide a valid approach to measuring soil conditions whereas other point by point methods continue to suffer from geospatial sparsity. Improving data collection methods such as using the vehicle as a sensor and consolidating common databases will be useful and addressed by the STANREC and AVT-327.

Soft soil simulation will also remain a critical investment requirement and understanding the range of soil types, and the effect of moisture (and other parameters, such as vegetation) on the soil trafficability is vital to its success. The STANREC will solidify lessons learned for side slope, drawbar pull, 3D terrain roughness metric, and methods of in-situ geotech data capture. The differences between model calibration and validation were demonstrated, which also highlighted the continuing important challenges in complex terramechanics. CT shows the most promise, but more research, development, and testing are needed in areas such as: CT soil model validation for all soil types (homogeneous and non-homogeneous), development of a calibrated CT soil models database (including moisture and temperature effects), and fundamental research into micro-scale soil models. Other research areas could include investigating/developing a soil classification system designed for vehicle mobility applications, and a terramechanics experiment to measure soil damping, viscosity, and dilation. There is also a need to improve the parallel scalability of the CT models and develop novel models for multi-layer terrains, water-covered, soft-soil terrains, heterogeneous terrains, vegetation, and urban obstacles. Vegetation, non-homogeneity, layers, geographic size, visibility, urban, slip-sinkage, multi pass, snow/ice/freeze, etc.

It should not be assumed that all implementations of NG-NRMM will have the same aspirational end state since there will be divergent requirements, and use cases will impact having a single solution. Although simple NG-NRMM has the greatest potential for exploitation across use cases, there will still be a case for a common, minimum NATO capability. A recommended Levels and Layers system will need to be adopted, and the STANREC will need to define Levels and refine Layers. Gaps and challenges other than terrain and soil, such as walking vehicles, small UGVs, vehicle data, utilizing NRMM2 legacy terrain will require different tools and novel solutions. The tools considered have demonstrated breadth against the new requirements but significant gaps and challenges remain.

## 7. Summary and Path Forward

Using modern methods, such as NG-NRMM, can significantly improve the ability to make more accurate mobility predictions and assessments which holds the promise of reducing prediction errors by an order of magnitude. There are simplified NG-NRMM solutions, running real time or better that can replace NRMM for use in operational planning, training, and field deployment. There are also high fidelity solutions which are suitable for research and development work at the technology and procurement level where statistics and confidence maps could be implemented. Although there has been significant progress in NG-NRMM development, further work and investment is needed to make it the new standard. Details of the nature of the data, how it was collected, what it represents, etc. can be found in [6].

The AMSP-06 STANREC will be an enduring artifact and development path for the NATO nation's mobility modeling methods, benchmarks and source databases that should be applied to physics based simulations of all operational land and amphibious mobility among the alliance. STANREC 4813 and AMPS-06 will be initially released to the NMSG (NATO Modeling and Simulation Group) for review, and a new RTG, AVT-327, will manage revisions and maintenance. AVT-327 is the forum in which many of the on-going issues will be delineated and planned for future clarification, and hopefully, resolved by, NATO itself, individual participating nations, or related independent software developers.

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