IDA | RESEARCH NOTES

THE WELCH AWARD 2016

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IDA is the Institute for Defense Analyses, a non-profit corporation operating in the public interest.

IDA's three federally funded research and development centers provide objective analyses of national security issues and related national challenges, particularly those requiring extraordinary scientific and technical expertise.

The summaries in this edition of IDA Research Notes, as well as the original articles, were written by researchers within the following six IDA divisions. The directors of those divisions would be glad to respond to questions about the specific research topics or related issues.

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IDA | THE WELCH AWARD

This issue of *IDA Research Notes* is dedicated to the winner and finalists of the 2016 Larry D. Welch Award for best external publication. Named in honor of IDA former president and U.S. Air Force Chief of Staff, General Larry Welch, the award recognizes individuals who exemplify General Welch's high standards of analytic excellence through their external publication in peer-reviewed journals or other professional publications, including books and monographs. The articles in this edition are executive summaries of the original published pieces. We have identified and credited the original publication for each article, and, where possible, we have included a link to the full piece.

Winner

In their article "Mining Measured Information from Text," IDA researchers **Arun Maiya, Dale Visser**, and **Andrew Wan** presented an approach to extract measured information from text especially involving search and exploration of scientific and technical documents. Their paper was published in the *Proceedings of the 38th International ACM SIGIR Conference on Research and Development in Information Retrieval*, August 2015.

Finalist

In support of the Military Compensation and Retirement Modernization Commission, IDA researchers **Sarah Burns, Philip Lurie**, and **Stan Horowitz** provided analyses to assist the Commission's considerations of potential modifications to the provision of health-related services. Their paper, *Analyses of Military Healthcare Benefit Design and Delivery: Study in Support of the Military Compensation and Retirement Modernization Commission*, was published in the *Final Report of the Military Compensation and Retirement Modernization Commission, Supporting Documents*, January 2015.

Finalist

IDA researcher **James Thorne** examined the convergence behavior of the series solutions to the Lambert problem over the range of possible transfer angles and flight times that approach the full period of the orbit in his article "Convergence Behavior of Series Solutions of the Lambert Problem," published in the *Journal of Guidance, Control, and Dynamics, Special Issue in Honor of Richard Battin*, 2015.

Finalist

In her book *Electoral Violence in Sub-Saharan Africa: Causes and Consequences*, published by First Forum Press, a division of Lynne Rienner Publishers, 2015, IDA researcher **Stephanie Burchard** explored how the persistence of electoral violence—and its causes and consequences—might affect the future of democracy in Africa.

Finalist

In the article "Orbital Debris Wire Harness Failure Assessment for the Joint Polar Satellite System," published in Procedia Engineering, *SciVerse ScienceDirect, The 13th Hypersonic Impact Symposium*, 2015, IDA researcher **Joel Williamsen** and co-author Steven Evans presented the results of two hypervelocity impact failure risk assessments for critical wire bundles exposed to an increased orbital debris environment aboard the Joint Polar Satellite System (JPSS-1).

Finalist

IDA researcher **David Alberts** made a distinction between the agility manifested by a system—a 'must-have' capability as systems are increasingly called upon to perform successfully—and a system's potential agility (its Agility Quotient–AQ) in his article "Systems Agility Quotient (AQ)," published in the *International Council of System Engineering Insight*, July 2014.

SELECTED OTHER NOMINATIONS

Four additional publications were called out by the Welch Award Selection Committee as being particularly noteworthy among the non-finalist papers for their high-quality research and success in the open literature.

In his article "Improved Error Estimation in Cases of Occasional Full Covariance," published in the *Proceedings of the 2015 IEEE Aerospace Conference*, March 2015, IDA researcher **Mark Briski** proposed an approach that uses the occasional transmitted full covariance to derive sensor position and compute model parameters. Once determined, the information can be used to create an estimated covariance for subsequent state vector updates that do not have full covariance. The original article can be found here: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7119117&newsearch=true&queryText=Improved%20Error%20Estimation%20in%20Cases%20of%20Occasional%20Full%20Covariance.

IDA researcher **Gregory Cox** considered the many problems faced by the Navy's Littoral Combat Ship (LCS), including the conceptual issues that hampered LCS acceptance outside (and inside) the Navy, so that plans for the new surface combatant can avoid those obstacles. His article "Lessons Learned from the LCS," was published in the *Proceedings of the U.S. Naval Institute*, January 2015. The original article can be found here: http://www.usni.org/magazines/proceedings/2015-01/lessons-learned-lcs.

A serious political crisis in Zimbabwe could affect U.S. interests in several ways, including significant humanitarian problems that could require an expensive U.S. aid commitment. IDA researcher and former ambassador to Namibia **George Ward**, in his article "Political Instability in Zimbabwe," published in the *Council on Foreign Relations, Center for Preventive Action, Contingency Planning Memorandum*, March 2015, identified options for the United States: intensifying interagency efforts to define U.S. interests in Zimbabwe, consulting closely with Southern African governments and China, and expanding communications with moderate members of the Zimbabwean political elite. The original article can be found here: http://www.cfr.org/zimbabwe/political-instability-zimbabwe/p36230.

In their article "Statistical Methods for Combining Information: Stryker Family of Vehicles Reliability Case Study," published in the *Journal of Quality Technology*, October 2015, IDA researchers **Rebecca Dickinson**, **Laura Freeman**, **Bruce Simpson**, and **Alyson Wilson** demonstrated that, when the available information across two test phases for the Stryker family of vehicles are combined, reliability estimates are more accurate and precise than those reported previously using traditional methods that employ only operational test data in their reliability assessments. The original article can be found here: https://secure.asq.org/perl/msg.pl?prvurl=http://asq.org/quality-technology/2015/09/statistical-process-control-spc/statistical-methods-for-combining-information-stryker-family-of-vehicles-reliability-case-study.pdf.

MINING MEASURED INFORMATION FROM TEXT

Arun Maiya, Dale Visser, and Andrew Wan

Many DoD problems involve the search and exploration of scientific and technical documents. In our work, we describe an approach to extract *measured information* from text (e.g., a 1370°*C* melting point, wavelengths greater than 2.4*μm*). We then present MQSEARCH, a search engine that leverages these extractions to provide full support for searches based on *measured information*. Together, these capabilities better allow DoD to make sense of large and unfamiliar sets of technical documents.

MQSEARCH is a facet-based navigation system that allows users to navigate large document sets based on measured quantities, measured properties, and the topics and themes with which they are associated. To the best of our knowledge, no other search engine in existence fully supports such a capability.

Scientific and technical documents describe methods and results using measured quantities: a numeric value paired with a unit of measurement. Examples of text snippets containing such measured quantities include the following:

- *average gravity curvature* $\zeta=(1.3999\pm0.003)x10^{-5}s^{-2}m^{-1}$
- *12°C melting point*
- *distance from Earth to the Sun is* $9.3x10^{7}$ *miles*
- *average responsivity as low as 6.2pA/K*

Note that these measured quantities (e.g., 6.2pA/K) are typically associated with a specific *measured property* (e.g., average responsivity). We studied ways in which to extract these kinds of *measured information* from documents.[1] The mining of such information is critically important across many domains – especially those involving search and exploration of scientific and technical articles. For instance, an optics researcher may wish to know whether the performance of Nd:YAG laser-pumped KTP parametric oscillators has ever been tested at wavelengths longer than 2.4*μm*. Full-text search engines using inverted indexes allow *ad hoc* queries on terms such as "KTP parametric oscillator," but the ability to further filter search results based on wavelengths greater than 2.4*μm* is not typically supported. To accomplish this, one must first identify and extract valid *measured quantities* (e.g., 2.4*μm*) in unstructured text and then identify and extract the *properties* being measured (e.g., *wavelength*). These extractions

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[1] We define measured information as measured quantities and the measured properties with which they are associated.

could then be stored in the index of a search engine in a way that supports subsequent document queries on measured information (e.g., faceted navigation, numeric range queries).

Surprisingly, there is very little existing work on how best to realize this process. Indeed, numerous challenges exist. For instance, there is a great deal of heterogeneity in how *measured quantities* and *measured properties* appear in text – both naturally and through corruption resulting from text conversion (e.g., converting a PDF to plain text). This, then, motivates the current investigation of how best to extract such information. Our contributions are as follows:

- We propose and describe a rule-based entity extractor to identify *measured quantities* in unstructured text documents. Our method includes an error-correcting procedure that recovers from aforementioned text conversion errors by 1) *reverse engineering* the corrupted and mangled measured quantities back to their original, correct form and 2) *standardizing* this form for storage in an inverted index and subsequent query processing.
- Using these extracted measured quantities, we show how to further extract the *measured properties* with which they are associated.
- Finally, we present MQSearch: the realization of a search engine with full support for *measured information*. MQSearch is a facet-based navigation system that allows users to navigate large document sets based on measured quantities, measured properties, and the topics and themes with which they are associated. To the best of our knowledge, no other search engine in existence fully supports such a capability.

We begin by describing the extraction of *measured quantities*.

MEASURED QUANTITIES

We view *measured quantities* as a 5-tuple of the form: (*sign, number, error, scientific notation, units*), where underlined elements are mandatory and others are optional. As an example, a team of researchers in Italy recently reported the first direct measurement of gravity's curvature as $(1.3999\pm0.003)\,x10^{-5}s^{-2}m^{-1}$ (Rosi et al. 2015). The corresponding 5-tuple representation of this[2] is

(<empty>, 1.3999, 0.003, 10-5, s-2m-1).

5-tuples such as this are populated using a series of extraction rules that operate on individual sentences. These rules fall into four broad categories: 1) pre-processing, 2) units, 3) quantities, and 4) post-processing. Simplified forms of some of the rules for units and quantities are shown in Table 1.[3] We refer to the algorithm implementing such rules as *Measured Quantity Extractor* or **MQE.** We begin with pre-processing rules.

[2] Since there is no explicit sign in this example, the first element is left empty.

[3] Rules are shown in Perl-like syntax, the *de facto* standard for regular expressions.

Table 1. [MQE Rules.] Simplified forms of some rules for extraction of measured quantities

Rule	Pattern	Example Matches
1) number	[+−]?(\d((\d?\d?[,]\d{2,3}([,]\d{2,3})*)|\d*))(\.(\d[\d\s]*\d|\d))?	1000.05, +5, -0.2, and 1,000
2) number (leading point)	[+-]?\.\d(\d\d(\s\d{3})+(\s\d{1,3})?|\d*)	-.98, .04, +.755
3) error	(\s{0,2} ± \s{0,2}[\d.]+)?	±0.003 in "1.3999 ± 0.003"
4) sci. notation.	(\s*[eE]|\s*([xX×])\s*10 *\^? [+-]?\d+)?	*e.g.*, forms of $\times 10^{-5}$: ×105, e-5, E-5
5) unit	*e.g.*, [fpnμmcdk]?m([\^]?[2-6] | [\-][1-6]) — $m^{\#}$ **normalized to** m^#	*μm*, *m*−1 (m^{-1}), *cm*2 (cm^{2}), *cm*^2
6) connector	(\s?/\s? | [Pp]er |-per-| |-\s× ·*])?	per, /, ·, ×
7) compound unit	<unit>(<connector><unit>)+	km/h, kilometer per hour,km·h^{-1}

Pre-Processing. As mentioned previously, when extracting text from various document formats (e.g., PDF, MS Office), characters often appear inconsistently. Minus signs, multiplication signs (e.g., x, ·), equal-like symbols (e.g., ≈, ≃, ≅), degree symbols, and the *μ* character can appear in a variety of ways or, in some cases, as "garbage" characters. For instance, minus can appear as the *en dash* character or appear corrupted as æ€. Pre-processing rules identify these variations in text and perform the necessary normalization for accurate extraction of units and quantities.

Units. *A measurement unit* preceded by a numeric string conforming to the 5-tuple structure is the base indicator of a measured quantity. Thus, to identify valid *measured quantities*, we constructed a comprehensive taxonomy of units from multiple public sources. Each unit has an associated rule. An example rule for *m* (i.e., symbol for meters) is shown in Rule 5 of Table 1. Note that such rules include optional prefixes for submultiples and multiples (e.g., *μ* before *m*, *kilo* before *meter*). Unit rules, when combined with pre-processing rules described previously, can accurately extract units under a range of noisy conditions. For instance, the corrupted unit *mâ*€1 is correctly recovered as m^{-1} by MQE. Finally, as shown in Rules 6 and 7, compound units are also supported (e.g., km/h, kilometer per hour, $s^{2}\cdot m^{-1}$).

Quantities. Like units, quantities (i.e., numbers with optional error ranges and scientific notation) can appear in a range of ways due to corruption and natural variation. These variations are collectively captured by rules such as those shown in Table 1 (i.e., Rules 1 through 4), which populate the remainder of the 5-tuple structure. As shown in Table 1, such rules capture a wide range of quantity formats (e.g., 10,000 with a comma, $1.3999 \pm 0.003 x 10^{-5}$ with both an error range and scientific notation, 1.23x105 with lost exponent in 10^{5}).

Post-Processing. We have already seen that text extracted from various document formats can be noisy. For instance, information from tables, headers, and figures can sometimes result in seemingly random sequences of numbers and letters in extracted text. In some cases, such information can be picked up erroneously by aforementioned rules as *measured quantities*. This is especially true for single letter units (e.g., *m* for meters, *A* for ampere). Post-processing rules are employed to reject such extractions and minimize false positives. Examples of such rejection rules include context-based rules (e.g., reject when preceded by "Table" or "Figure"), repetition-based rules such as rejecting compound units consisting of repeated single letter units (e.g., 3 AJmm), and allowing a dash only between certain quantities and units (e.g., *10-cm* is okay but not *10-A*).

MEASURED PROPERTIES

We now turn our attention to the extraction of *measured properties*. To better illustrate the problem, we show several example snippets containing *measured quantities*. In each example, the measured quantity is shown in blue, the *property* being measured is highlighted in red, and the characters connecting them are underlined:

- *a pixel pitch as high as roughly 352μm*
- *a 352μm pixel pitch*
- *The pixel pitch employed was 352μm.*
- *average gravity curvature ζ=(1.3999±0.003)x10⁻⁵s⁻²m⁻¹*
- with *50mL of 30% fuming sulfuric acid*
- *size* ≅ 0.1m²
- *frequency of longitudinal scan was approximately 300 Hz*
- *a nominal current density of 1.3 A/cm² to 0.03 A/cm²*
- *panel strength lower than 8.90 ksi (61.4 MPa)*
- *wavelengths at least 2.4μm*
- *large fields of about, or above 10 kV/cm*

From just the examples shown, it is easy to see that there is a high degree of variability in the words connecting a *measured property* with a *measured quantity*. However, upon closer inspection, we find that this variability can be reduced to a small number of syntactic patterns based on parts of speech (POS) that capture most scenarios. Table 2 shows some syntactic patterns that we employ to extract *measured properties*. We refer to the extractor applying such syntactic rules as *Measured Property Extractor* or **MPE**. The notation shown here employs the Penn Treebank format, which associates tags with POS (e.g., NP represents a noun phrase). In addition, the EQ tag represents all symbols related to '=' (e.g., ≈,≃), and the SYM tag matches one or two character symbols (e.g., a Greek letter).

EXPERIMENTAL EVALUATION

We evaluated our approach on a text corpus consisting of 40,807 unclassified technical reports published in the 2008–2010 time frame and hosted by the Defense Technical Information Center (DTIC). This rich collection describes a wide range of research funded by the DoD spanning numerous fields from engineering and physical science to biomedical research and social

Table 2. [MPE Rules.] Simplified forms of some syntactic patterns to extract measured properties

<table>
<tr><th>Pattern</th><th colspan="2">Example Matches (two examples shown for each rule)</th></tr>
<tr><td>NP SYM{0,2} EQ mq</td><td>1) gravity curvature $\zeta = 1.4 \times 10^{-5} s^{-2} m^{-1}$</td><td>2) floor area ≊ $32m^2$</td></tr>
<tr><td>mq IN? NP</td><td>1) a 352 μm pixel pitch</td><td>2) 50mL of 30% fuming sulfuric acid</td></tr>
<tr><td>NP IN DT? NP VP+ (TO|IN|RB|JJ)* mq</td><td>1) strength of panel was set to 9 ksi</td><td>2) freq. of scans was roughly 300 Hz</td></tr>
<tr><td>NP (IN DT? NP)* VP+ (IN|TO|RB|JJ)* mq</td><td>1) pixel pitch employed was 352 μm.</td><td>2) panel strength was recorded at 9 ksi.</td></tr>
<tr><td>NP (CC|IN|TO|RB|JJ)* \(?mq\)?</td><td>1) wavelengths of at least 2.4 μm</td><td>2) panel strength (9 ksi)</td></tr>
</table>

science. Table 3 shows the precision and recall estimates for both the MQE and the MPE over the entire corpus.

Table 3. 95% Confidence Intervals for precision and recall when extracting measured quantities (using MQE) and measured properties (using MPE) from the DTIC corpus.

Extractor	Precision	Recall
MQE	(0.93, 0.99)	(0.92, 0.99)
MPE	(0.93, 0.97)	(0.88, 0.94)

As can be seen in the table, both MQE and MPE perform extraordinarily well in extracting *measured quantities* and the *properties* they describe from documents across disparate fields. Having demonstrated the success with which *measured information* can be mined, we now demonstrate how these extractions can be exploited in novel search applications.

AN APPLICATION: MQSEARCH

MQSEARCH is a realization of a search engine with full support for *measured information*. MQSEARCH is implemented using Apache Solr,[4] which supports full-text search, faceted navigation, and numeric range queries. During the process of indexing and ingesting the DTIC document set into our search engine, we apply our extractors to encountered text and store both *measured quantities* and *measured properties* in the search engine index. In addition, the search engine performs keyphrase extraction on documents using the KERA algorithm (Maiya et al. 2013). Using Solr facet queries, extracted keyphrases can be used to produce a tag cloud for any subset of the document set. Figure 1 shows the faceted navigation panel of MQSEARCH, which allows users to filter documents based on discovered measurement units, quantity ranges, and measured properties. In Figure 1, the measurement unit *U/mL* is selected. We see that there are 153 documents (out of roughly 40,000) mentioning this unit with quantities ranging from 0.001 U/mL to 10,000 U/mL. The property most frequently measured in *U/mL* is *penicillin*. From the tag cloud, we see that documents containing quantities measured in U/mL tend to

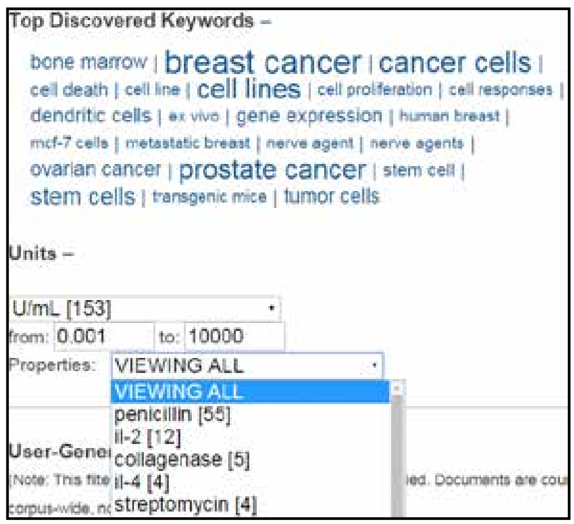

Figure 1. [MQSEARCH.] The measurement unit U/mL is selected, which reveals the associated topics (e.g., breast/prostate cancer), associated measured properties (e.g., concentrations of penicillin), and associated quantity ranges (i.e., 0.001 to 10,000)

[4] http://lucene.apache.org/solr/.

cover topics such as breast cancer and prostate cancer research. The search results can be filtered further along any of these dimensions. To the best of our knowledge, ours is the first search engine with such support for *measured information.*

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IDA President Dr. David S.C. Chu with the winners of this year's Welch Award: Dr. Wan, Dr. Maiya, and Dr. Visser.

The original article was published in the *Proceedings of the 38th International ACM SIGIR Conference on Research and Development in Information Retrieval*, August 2015.

Mining Measured Information from Text

http://dl.acm.org/citation.cfm?id=2766462&picked=prox

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MILITARY HEALTHCARE BENEFIT DESIGN AND DELIVERY

Sarah Burns, Philip Lurie, and Stan Horowitz

Over the last decade, personnel costs have been the fastest rising component of the Department of Defense (DoD) budget, driven to a considerable degree by healthcare. Concerned about the impact of rising healthcare and other personnel costs on military readiness, the Congress established the Military Compensation and Retirement Modernization Commission (MCRMC) to perform a systematic review of the military compensation and retirement systems and to make recommendations for modernization.

IDA was asked to support the MCRMC in their consideration of potential modifications to the provision of health-related services. We estimated the cost of an alternative way of providing care to a large segment of DoD's beneficiary population: dependents of military personnel, retirees, and their dependents.

Currently this population is served through a combination of care provided in DoD-owned and -operated facilities and care purchased in the private sector through the TRICARE system. Under TRICARE, DoD purchases care on a fee-for-service basis at no or very low cost to beneficiaries. The design of TRICARE does not encourage economical use of medical services by either patients or health care providers.

We compared the cost of continuing to use TRICARE with the cost of providing health care through a system like the Federal Employees Health Benefit Program (FEHBP).

We compared the cost of continuing to use TRICARE with the cost of providing health care through a system like the Federal Employees Health Benefit Program (FEHBP), the one available to DoD civilians and other U.S. government employees. The specific options available under FEHBP vary by state, but, in general, it offers a menu of plans with different characteristics regarding cost and coverage from which employees can choose.

Using the observed enrollment behavior of the FEHBP civilian population in conjunction with demographic data on the DoD beneficiary population, we developed a simple cohort-based methodology to predict the plan enrollment behavior that would result if DoD were to purchase healthcare through an FEHBP-like program. A series of analytically derived adjustments to FEHBP plan premiums to reflect the health risk of the DoD population was also developed. Plan choice and premiums were then used to construct the total cost of covering the relevant beneficiary population through this FEHBP-like model. The final cost estimate indicated that the population could be covered for approximately $18 billion per year. This figure represents the estimated cost of delivering care in steady state equilibrium after allowing for a period of transition.

We then estimated the cost of covering the same beneficiary population under TRICARE. We included all costs incurred while delivering care that would be covered by premiums under a private health insurance model. We calculated the cost of coverage under TRICARE to be approximately $21.2 billion, suggesting budgetary cost savings in the range of $2 billion to $4 billion, with a best estimate of just over $3 billion.

These savings, however, do not reflect the full value of switching to a private health insurance model because benefit quality would rise under the new FEHBP-like benefit. To account for the increase in quality, we developed an analytical concept to approximate the full potential savings that would result if benefit quality were held constant between the current TRICARE model and the proposed FEHB like model. We call this concept the "full cost savings" from switching to private health insurance and estimated that it would equal about $7.5 billion.

The MCRMC recommended the adoption of an FEHBP-like plan in its report to the President and Congress.

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Dr. Lurie is a Research Staff Member in IDA's Cost Analysis and Research Division. He holds a Doctor of Philosophy in statistics from Harvard University.

Mr. Horowitz is an Assistant Director in IDA's Cost Analysis and Research Division. He holds a Master of Arts in economics from the University of Chicago.

The original IDA publication (IDA Paper P-5213, *Analyses of Military Healthcare Benefit Design and Delivery: Study in Support of the Military Compensation and Retirement Modernization Commission*) was published in the Final Report of the Military Compensation and Retirement Modernization Commission, Supporting Documents, January 2015.

CONVERGENCE BEHAVIOR OF SERIES SOLUTIONS OF THE LAMBERT PROBLEM

James Thorne

Lambert's problem, to find the unique conic trajectory that connects two points in a spherical gravity field in a given time, is represented by a set of transcendental equations due to Lagrange. The associated Lagrange equations for the orbital transfer time can be expressed as series expansions for all cases. Power series solutions have been published that reverse the functionality of the Lagrange equations to provide direct expressions for the unknown semi-major axis as an explicit function of time. The convergence behavior of the series solutions is examined over the range of possible transfer angles and flight times. The effect of arbitrary precision calculations is shown on the generation of the series coefficients.

Lagrange's equations (or other reformulations of them) must be supplemented by some sort of root-finding technique to form a complete solution.

Lagrange derived a set of transcendental equations that determine the time of flight on an orbital trajectory as a function of the semi-major axis of the conic section that connects two points in a spherical gravity field. However, in the Lambert problem, the semi-major axis is desired as a function of the given time of flight rather than the reverse, so Lagrange's equations (or other reformulations of them) must be supplemented by some sort of root-finding technique to form a complete solution. Alternatively, power series have been published (Thorne 2004) that algebraically reverse the functionality of the Lagrange equations to provide a direct solution for the unknown semi-major axis as an explicit function of the given time of flight.

The article examined the convergence behavior of the series solutions to the Lambert problem over the range of possible transfer angles and flight times that approach the full period of the orbit. Also, the effect of arbitrary precision arithmetic was shown for the calculation of the series coefficients.

BACKGROUND – SERIES SOLUTIONS OF THE LAMBERT PROBLEM

For convenience, the series solutions of the Lambert problem (Thorne 2004) are repeated here for the discussion of convergence properties. Lambert's theorem states that the orbital transfer time (t) between two known positions in the 2-body orbital problem is dependent only on the semi-major axis (a), given two fixed position vectors and a known gravitational constant. Lagrange proved this theorem and derived elegant equations that show this functional dependence (Battin 1987, 287). Apart from the limiting cases of straight-line and parabolic transfers, the possible orbital paths fall into three categories: Hyperbolic, A-type elliptical, or B-type elliptical. Hyperbolic transfers take less time than the unique parabolic solution, A-type elliptical transfers take longer than the parabolic time but less than minimum-energy time, and B-type elliptical transfers take longer than minimum-energy time. Also, a leading number 1 or 2 will indicate whether the transfer angle is less than 1 or greater than 2 π radians. Thus, the possible transfer types (1H, 2H; 1A, 2A; and 1B, 2B) are apart from the exact parabolic and minimum-energy cases that can be calculated from the given inputs to the Lambert problem. Typically, A-type elliptical transfers involve orbital arcs that connect position vectors going the "short way" around the ellipse, while B-type transfers generally go the "long way" around the ellipse. Although this language is commonly used to describe elliptical orbit arcs, care should be used to select the correct version of the Lagrange equations based on time and transfer angle as explained above. The basic problem geometry is shown in Figure 1.

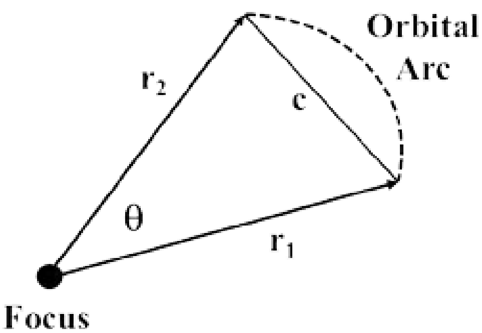

Figure 1. Lambert Problem Geometry

If the transfer angle is less or more than π radians, there is a corresponding sign change (±) in the Lagrange equation, as shown in Eq. 1:

$$\text{1A, 2A:}\quad t = \frac{\sqrt{a^3}}{k}\{(\alpha - \sin\alpha) \mp (\beta - \sin\beta)\}$$

Eq.1

where

$$\alpha = 2\sin^{-1}\sqrt{\frac{s}{2a}}, \beta = 2\sin^{-1}\sqrt{\frac{s-c}{2a}}$$

Eq. 2

In Eq. 2, c is the chord, which is a line segment connecting the two observed position vectors, and s is one-half the sum of the lengths of the position vectors and the chord, $s = (r_1 + r_2 + c)/2$ as shown in Figure 1. The gravitational constant is k. These quantities are known from the given observations and are not dependent on the transfer time, t_p. The unique parabolic flight time for a given geometry, t_p, is given by Eq. 3, and the unique minimum-energy flight time can be found from Eqs. 1 and 2 by letting $a = s/2$.

$$t_p = \frac{\sqrt{2}}{3}\frac{s^{3/2}}{k}\left((1 \mp \left(\frac{s-c}{s}\right)^{3/2}\right)$$

Eq.3

Many excellent iterative techniques exist to solve the Lagrange equations. (Thorne and Bain 1995). However, since a is the unknown quantity to be found, it would be quite useful to find a direct solution to avoid the need for any type of root-finding technique. Series reversion may be used to solve Eq. 2 as follows:

$$a = \left(\frac{s}{2}\right) \sum_{n=0}^{\infty} \frac{B_n}{[\mathrm{H, A}]} \left(\frac{t}{t_p} - 1\right)^{n-1}$$

Eq.4

However, series reversion may result in a small radius of convergence as well as numerical errors in the calculation of high-order terms. Next, we address the effect of machine precision on the evaluation of Eq. 4.

EFFECT OF MACHINE PRECISION ON THE HYPERBOLIC AND SHORT-WAY ELLIPTIC SERIES

The series solution for the hyperbolic and short-way elliptic cases, Eq. 4, originally appeared to be asymptotically convergent (Vallado 2001, 476–485). As described by Dr. Richard H. Battin in conversations with the author in 1990, asymptotic convergence occurs when a divergent series can produce useful results at limited orders because the initial behavior is convergent prior to later growth of the series terms, which was the case for Eq. 4. However, based on recent numerical experiments using arbitrary precision, the series appears to behave in a convergent manner because the growth in higher order terms was apparently a result of machine precision limitations based on the technology of the time and not due to asymptotic convergence.

As a numerical example of the Lambert problem using earth-based physical units, consider an object in earth orbit with two known position observations and a transfer time. Suppose that the magnitudes of the position vectors are r_1 = 8000 km and r_2 = 8010 km, the transfer angle is 140°, and the earth's gravitational constant is 398600.44144982 km^3/s^2. If the observed time of flight of the orbital transfer is exactly 2550 s, the goal is to determine the semi-major axis of the unknown orbit. This is an example of a short-way elliptical transfer, which can be solved using Eq. 4 with arbitrary precision calculations to demonstrate the improvement over finite precision calculations.

Table 1 shows the cumulative effect of numerical precision of using finite precision (FP) calculations vs. arbitrary precision (AP) calculations to determine the values of the series coefficients, series terms, and partial sums. In this case, finite precision calculations maintained 17 digits based on an extended real variable declaration in the original Pascal programming language. Using arbitrary precision with a symbolic manipulation program such as Mathematica (MMA) effectively removes the limit on the precision level of the calculations by setting it to any level desired.

The first column in Table 1 shows the index in the series, the second and third show the series coefficients, the fourth and fifth show the value of the full series term with the time argument, and the sixth and seventh show the partial sums that are the calculated value of semi-major axis in kilometers. The series coefficients, B_n, show good agreement through an index value of 23. Under finite precision, the B_n begin to diverge above an index value of 23, whereas they continue to converge indefinitely

Table 1. Example History of Series Behavior – Comparison of Finite Precision (FP) vs. Arbitrary Precision (AP) Results to Order 35

Index	FP b[n]	AP b[n]	FP term[n]	AP term[n]	FP sum (km)	AP sum (km)
1	2341.5257009	2341.5257009	3021.9126260	3021.9126260	3021.9126260	3021.9126260
2	4159.7690280	4159.7690280	4159.7690280	4159.7690280	7181.6816540	7181.6816540
3	1549.5393497	1549.5393497	1200.6588744	1200.6588744	8382.3405283	8382.3405283
4	-167.2452322	-167.2452322	-100.4125041	-100.4125041	8281.9280242	8281.9280242
5	51.1296198	51.1296198	23.7861219	23.7861219	8305.7141462	8305.7141462
6	-21.2401119	-21.2401119	-7.6564051	-7.6564051	8298.0577411	8298.0577411
7	10.3514416	10.3514416	2.8912521	2.8912521	8300.9489932	8300.9489932
8	-5.6117878	-5.6117878	-1.2145164	-1.2145164	8299.7344768	8299.7344768
9	3.3174596	3.3174596	0.5563202	0.5563202	8300.2907970	8300.2907970
10	-2.1288137	-2.1288137	-0.2766138	-0.2766138	8300.0141832	8300.0141832
11	1.4838952	1.4838952	0.1494020	0.1494020	8300.1635852	8300.1635852
12	-1.1208531	-1.1208531	-0.0874418	-0.0874418	8300.0761434	8300.0761434
13	0.9078658	0.9078658	0.0548793	0.0548793	8300.1310228	8300.1310228
14	-0.7747516	-0.7747516	-0.0362883	-0.0362883	8300.0947344	8300.0947344
15	0.6827783	0.6827783	0.0247800	0.0247800	8300.1195144	8300.1195144
16	-0.6102833	-0.6102834	-0.0171621	-0.0171621	8300.1023524	8300.1023524
17	0.5453631	0.5453631	0.0118834	0.0118834	8300.1142358	8300.1142358
18	-0.4819197	-0.4819210	-0.0081367	-0.0081367	8300.1060991	8300.1060991
19	0.4174042	0.4174044	0.0054607	0.0054607	8300.1115598	8300.1115597
20	-0.3514535	-0.3514281	-0.0035627	-0.0035624	8300.1079971	8300.1079973
21	0.2850735	0.2848903	0.0022391	0.0022377	8300.1102362	8300.1102350
22	-0.2205273	-0.2193769	-0.0013422	-0.0013352	8300.1088941	8300.1088999
23	0.1621976	0.1567467	0.0007649	0.0007392	8300.1096590	8300.1096391
24	-0.1279172	-0.0988385	-0.0004674	-0.0003612	8300.1091916	8300.1092779
25	0.1347753	0.0472689	0.0003816	0.0001338	8300.1095732	8300.1094117
26	-0.3354922	-0.0032989	-0.0007360	-0.0000072	8300.1088371	8300.1094045
27	0.6277174	-0.0322417	0.0010671	-0.0000548	8300.1099042	8300.1093497
28	-0.8371108	0.0589831	-0.0011026	0.0000777	8300.1088016	8300.1094274
29	4.1027220	-0.0770060	0.0041873	-0.0000786	8300.1129889	8300.1093488
30	-37.2049232	0.0868005	-0.0294223	0.0000686	8300.0835665	8300.1094174
31	305.7985549	-0.0892027	0.1873826	-0.0000547	8300.2709491	8300.1093628
32	-2017.8173395	0.0853155	-0.9580598	0.0000405	8299.3128893	8300.1094033
33	8919.4675674	-0.0764208	3.2814571	-0.0000281	8302.5943464	8300.1093752
34		0.0638904		0.0000182		8300.1093934
35		-0.0490998		-0.0000108		8300.1093825

using arbitrary precision. At index value 35, the last partial sum using arbitrary precision results in a 8300.1093825 km for semi-major axis, which is correct to less than 1 meter. Substituting this value for the semi-major axis in the original Lagrange time-of-flight Eq. 1 as a check, the resulting transfer time is 2550.000002 s. The data from Table 1 can also be graphed to show the beneficial effect of arbitrary machine precision, as seen in Figure 2.

In Figure 2, the magnitude of the series terms is plotted against the index value. The first curve, denoted "Pascal," was generated with a finite precision Pascal compiler, and the numerical results were included in Table 1 based on the previous discussion. The second curve, denoted "MMA" was generated in Mathematica with no limit on arithmetic precision, and those data were also included in Table 1. The two curves are shown with the same vertical scale to emphasize the dramatic difference in their behavior, and very significantly to show the important result that the power series solution is convergent rather than divergent, as had been previously assumed based on earlier numerical research using finite precision arithmetic. In short, this result confirms the numerical utility of the power series solution for the Lambert Problem of initial orbit and trajectory determination.

The magnitude of the coefficients continues to decrease uniformly out to 150 terms as shown in Figure 2 and to more than 300 terms based on additional numerical experiments, making the series solution much more useful at high order. As the index value gets near to the number digits of machine

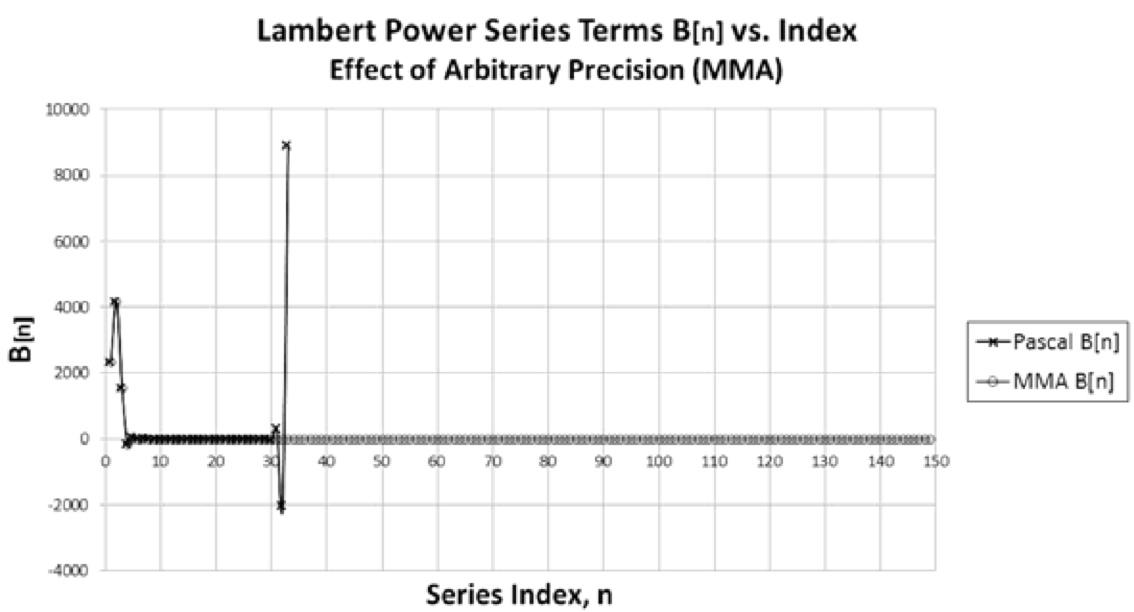

Figure 2. Effect of Arbitrary Precision on Convergence

precision, the calculations can lose significance because the algorithm produces small differences between very large numbers. Arbitrary precision arithmetic addresses this problem, so there is no loss in precision during the arithmetic calculations.

In Figure 3, the series coefficients are shown at a much smaller scale than in Table 1 in order to see the convergence behavior in detail. It can be seen that the series coefficients have alternating signs and exhibit a beat phenomenon in the sinusoidal decay of their magnitudes.

expansion about the region where the semi-major axis approaches infinity on a parabolic transfer, so the accuracy of the series solution is best near the parabolic time. The second series solution to the Lagrange equations uses an expansion about the point where the semi-major axis reaches its minimum positive value, which corresponds physically to a minimum-energy transfer arc. This series solution provides a reasonably accurate solution for the range from the minimum-energy transfer time up to a transfer time that is approximately 1.5 times the minimum-energy transfer time, based on numerical investigation. The

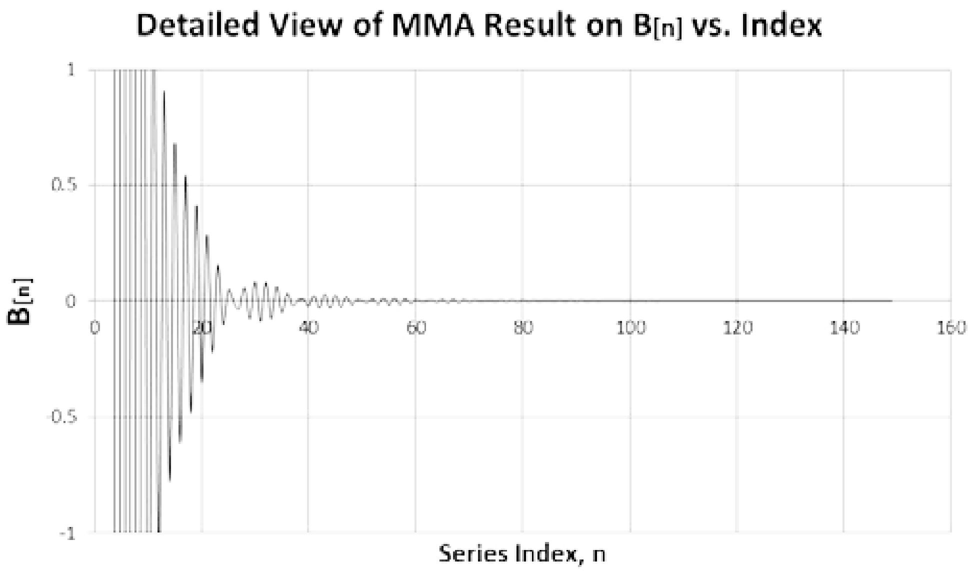

Figure 3. Detail of Series Convergence Behavior

CONCLUSIONS

The series solutions for the Lambert problem show good convergence properties near their expansion points, as would be expected. The first series solution to the Lagrange equations uses an third series solution to the Lagrange equations uses an expansion about the region where the semi-major axis approaches infinity as the transfer time also approaches infinity. Physically, this means that the transfer time approaches the period of the closed orbit.

For the series solution for the hyperbolic and short-way elliptic cases, a combination of series reversion and inversion results in better convergence properties than reversion alone. However, this series will appear to be asymptotically convergent if the coefficients are calculated using finite precision arithmetic. Based on numerical investigation, this divergent behavior completely disappears out to 300 terms when using arbitrary precision calculations, which would suggest that the series solution is actually convergent.

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Convergence Behavior of Series Solutions of the Lambert Problem

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ELECTION TRENDS IN AFRICA

Stephanie Burchard

Beginning in the late 1980s, a seismic political shift took place in sub-Saharan Africa. In rapid-fire succession, autocratic regimes fell and were replaced by (at least notionally) democratic regimes. Whereas only a handful of countries in Africa could have been considered democratic in 1990, by 1997 approximately 75 percent of countries set out on a path of democratization by adopting multiparty elections (Adejumobi 2000). Unfortunately, violence has been a regular and persistent feature of many elections held in Africa since 1990. What accounts for this trend and what impact has it had on democratic development in Africa?

Elections are a way to manage conflict over access to political power in a way that, ideally, should prevent or preclude the outbreak of violence. Many elections, unfortunately, often fall short of the ideal.

Electoral violence is any act of harassment or intimidation that is either intentionally or incidentally meant to affect the outcome of an election. Actors include state security forces, opposition supporters, partisan operatives, youth group militias, and thugs hired by politicians. Violence can occur either before or after the results are announced. Pre-election violence is generally more prevalent, but post-election violence is more deadly. Incidental violence is not planned but rather occurs as the result of heated or emotionally charged elections and happenstance (e.g., protests turn into riots, security forces respond to protesters with excessive force). Strategic violence, on the other hand, is planned in advance. Examples include political assassinations, attacks on an opposition meeting or rally, thugs dispatched through neighborhoods to threaten citizens to vote, people forced to flee communities due to threats or actual violence (arson frequently gets the message across). Violence has the ability to spread quickly and affect citizens and institutions exponentially.

Elections are a way to manage conflict over access to political power in a way that, ideally, should prevent or preclude the outbreak of violence. Many elections, unfortunately, often fall short of the ideal. Globally, roughly 19 percent of elections experience violence (Norris 2012). In sub-Saharan Africa, this number is substantially higher by a magnitude of between two and three orders. Building on previous data collected by colleagues, I compiled information on election violence in all elections held in sub-Saharan Africa between 1990 and 2014—289 elections in total. I estimate that, on average, between 50 and 60 percent of elections held in Africa can be considered violent.

African experiences are instructive for understanding the how and why of electoral violence more broadly because of the many similarities and differences found across sub-Saharan Africa's 48 countries. Many countries share common colonial histories, and post-colonial trends have tended to come in waves; however, differences across the countries in terms of specific political institutions and democratic trajectories provide analytic leverage that helps identify the causes and consequences of electoral violence.

Several countries have little if any experience with electoral violence. These countries include Benin, Botswana, Cape Verde, and Mauritius. The majority of election violence (65 percent) is of the low-grade variety, characterized by violent harassment and intimidation. Elections in Cameroon, Djibouti, Gabon, Gambia, and Swaziland frequently fit into this category. Targeted assassinations and prolonged imprisonment of opposition members occur in 19 percent of violent elections. Burundi, Equatorial Guinea, Ethiopia, Sudan, and Uganda often experience these types of electoral incidents. Widespread generalized violence with numerous fatalities, typically ranging from several dozen to several thousand, occurs in 16 percent of violent elections. Examples include the 2007–2008 post-election violence in Kenya, in which upwards of 1,500 were killed and 660,000 were displaced; Côte d'Ivoire's 2010 election crisis, which resulted in approximately 3,000 deaths in the months after the election; and the 2011 Nigerian election in which more than 800 died. Adding to this complexity, while there are trends in which countries typically experience violent elections, there is substantial in-country variation from election to election. Kenyan elections are typically violent, but not always, and some elections are more violent than others.

Countries with non-violent elections tend to score better on indices that measure political freedoms, civil liberties, adherence to rule of law, and political accountability. More inclusive electoral institutions, such as proportional representation, are associated with lower rates of electoral violence. Conversely, elections held in less-than-democratic settings—where rule of law is weak, political freedoms are curtailed, and accountability is weak—are generally more violent than not. Presidential elections are typically more violent than legislative elections, but violence is not exclusive to one or the other. It is often obscured by the high-profile nature of presidential elections, but legislative aspirants utilize election violence as well.

Electoral institutions that have a low threshold for victory, such as plurality rules in single member districts, are more prone to violent outbreaks. Finally, electoral fraud and electoral violence are highly correlated and seem to be complementary electoral strategies and fodder for violent protestation of electoral results.

Beyond the obvious concern for human life, electoral violence is problematic for a number of reasons. First, in a worst case scenario, civil war or a deadly political conflict that requires international mediation has broken out following a number of contentious elections including Angola in 1992, Republic of Congo in 1994, Togo in 2005, Kenya in 2007, Zimbabwe in 2008, Côte d'Ivoire in 2010, and Nigeria in 2011. However, there are also associated risks with elections that experience even low levels of violence. These types of elections are related to lower levels of satisfaction with democracy, support for democracy, and trust in democratic institutions at the individual level. It is in this way that electoral violence can eat democracy alive from the outside-in by targeting those whose consent democratic development depends heavily upon: the citizens.

What can be done? My research suggests several ways to reduce incidences of electoral violence, all of which work to increase trust in the electoral process and build consensus among key actors in the electoral arena. First, robust domestic observation that includes critical buy-in from political parties, the press, and civil society can go a long way to decreasing the likelihood of electoral violence. Second, ancillary electoral institutions need to be supported. Independent electoral management bodies and strong judiciaries are related to more peaceful elections. Finally, working to reduce the winner-take-all mentality of elections can also de-escalate electoral tensions and prevent violence. Decentralizing political power, by creating local government bodies and adopting consensus-building electoral rules that require manufactured majorities, can reduce electoral stakes and the incentives for violence.

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ASSESSING ORBITAL DEBRIS WIRE HARNESS FAILURE FOR THE JOINT POLAR SATELLITE SYSTEM

Joel Williamsen and Steven Evans

This article estimates the likelihood of orbital debris (OD) penetration of wire harnesses aboard the Joint Polar Satellite System (JPSS) using computer hydrocode modeling techniques, combined with an understanding of the orbital debris distribution predicted by NASA's Orbital Debris Model (ORDEM 3.0), and an estimate of redundancy of critical wires in typical 6, 18, and 36 strand cables. Based on the unacceptable risk levels associated with these initial results, the article describes an improved protective blanket design that reduced OD penetration risk to acceptable program levels.

NASA's new orbital debris environment (ORDEM 3.0) includes an order of magnitude increase in particle counts in the 1millimeter size range, and a huge increase in stainless steel particles, which are denser and therefore more penetrating than aluminum particles assumed in prior orbital debris models (Squire et al. 2014). In light of this more challenging environment, the NASA Engineering and Safety Council (NESC) sponsored an independent assessment of the orbital debris protection offered by the Joint Polar Satellite System (JPSS-1) in the summer of 2014.

The JPSS-1 spacecraft wiring is exposed to orbital debris on the zenith deck of the spacecraft, as shown in Figure 1. Some of this wiring supports critical functions that would be required to ensure reentry of the satellite at the end of its life. As part of its support, several members of our NESC team developed and implemented a generic approach for determining the risk of critical function loss from hypervelocity impact and penetration of critical wire bundles from steel and aluminum orbital debris particles impacting from 7.3 to 14.6 kilometers/second. This initial assessment showed an extremely high likelihood of orbital debris penetration per linear meter of exposed wiring, even accounting for potential redundancies.

The NASA Engineering and Safety Council (NESC) sponsored an independent assessment of the orbital debris protection offered by the Joint Polar Satellite System (JPSS-1). This initial assessment showed an extremely high likelihood of orbital debris penetration per linear meter of exposed wiring

Based on this high computed risk of wire failure, the team designed an enhanced orbital debris protection design consisting of betacloth-reinforced multi-layer insulation (MLI) suspended at a 5-centimeter standoff over a 7-layer

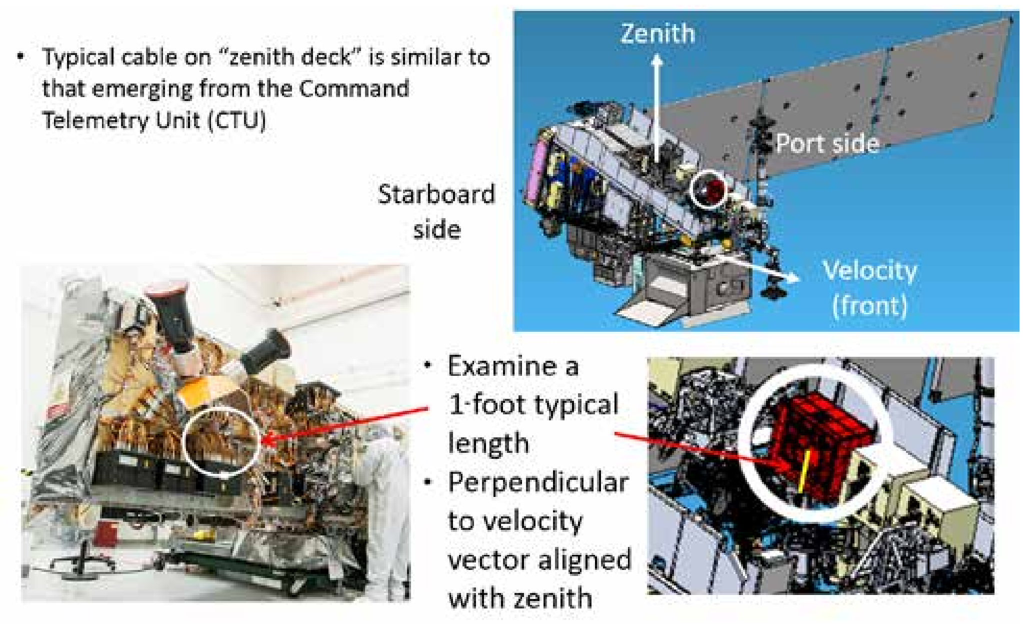


Figure 1. JPSS-1 Wire Harness Geometry, Location and Orientation in SPH Hydrocode Risk Assessment

betacloth and Kevlar blanket, which was draped over the exposed wire bundles. A second Smooth Particle Hydrodynamics (SPH)-based risk assessment was conducted; it also included the beneficial effects from the high (75 degree) obliquity of orbital debris impact and shadowing by other spacecraft components. The result was a considerably reduced likelihood of critical wire bundle failure compared to the original baseline design. This second approach is consistent with earlier wire failure assessments for the James Webb Space Telescope (NASA Engineering and Safety Panel 2008) and other spacecraft such as the Advanced Xray Astrophysics Facility (NASA Presentation 2008), which assumed that any penetration of the shield over the wire bundle caused failure of the bundle.

TASK 1: "GENERIC" RISK ASSESSMENT OF BASELINE MULTI-LAYER INSULATION OVER WIRE BUNDLES

To conduct this effort, our IDA team performed Smooth Particle Hydrodynamics in C computer code (SPHC) hydrocode assessments of orbital debris penetration through a "typical" wire harness (cable) with baseline MLI blanket protection. The SPHC hydrocode is a C language implementation developed by Stellingwerf (1985–1995). In smooth particle hydrodynamics, the "particle" is the analog of the mesh point in a traditional hydrocode. An SPH particle consists of a fixed mass of material at a given position in space, together with a smoothing function, or "kernel," that defines the particle's extent.

Figure 2 shows a typical cable consisting of 36 wires (18 redundant wire pairs), where every wire is considered critical to the function of the cable—that is, if any redundant pair is destroyed. The wires were placed in a hexagonal pattern in order to scale the damage seen in 36 wires to smaller wire bundles (of 18 and 6 wires, respectively). To retain symmetry, the actual hexagonal patterns undergoing hydrocode assessment were of 37, 19, and 7 wires, with damage to the last (deepest) wire neglected in the risk results for the 36-, 18-, and 6-wire strands. The risk assessment considered a one-year exposure to the ORDEM 3.0 orbital debris environment with a zenith/nadir wire orientation. A 5-centimeter standoff of baseline MLI to wire harness (cable) was included in the hydrocode run.

Figures 2 and 3 show typical results from the SPH analyses of the number of wires cut, considering a variety of orbital debris impact materials, velocities and diameters. Note that the expected number of penetrated wires increases with velocity, diameter, and density of the projectile. Figure 4 shows the likelihood of an entire cable failing based on the number of redundant wire failures. As shown, once more than half of the wires (i.e., 19 wires in a 36-wire bundle) are penetrated, there is a 100 percent chance that two redundant wires have been hit, thus "killing" the critical instrument that the wire is feeding. The likelihood of critical instrument failure increases with the number of wires penetrated until unity (100 percent) is reached when penetrating more than half the wires.

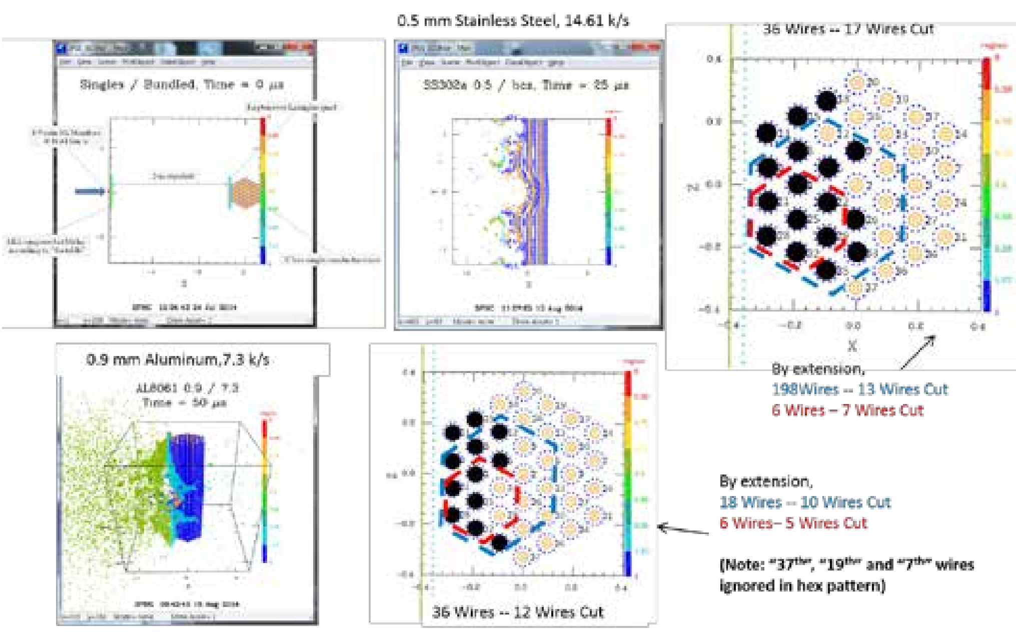


Figure 2. Typical SPH Hydrocode Predictions for Steel and Aluminum Orbital Debris Impacts

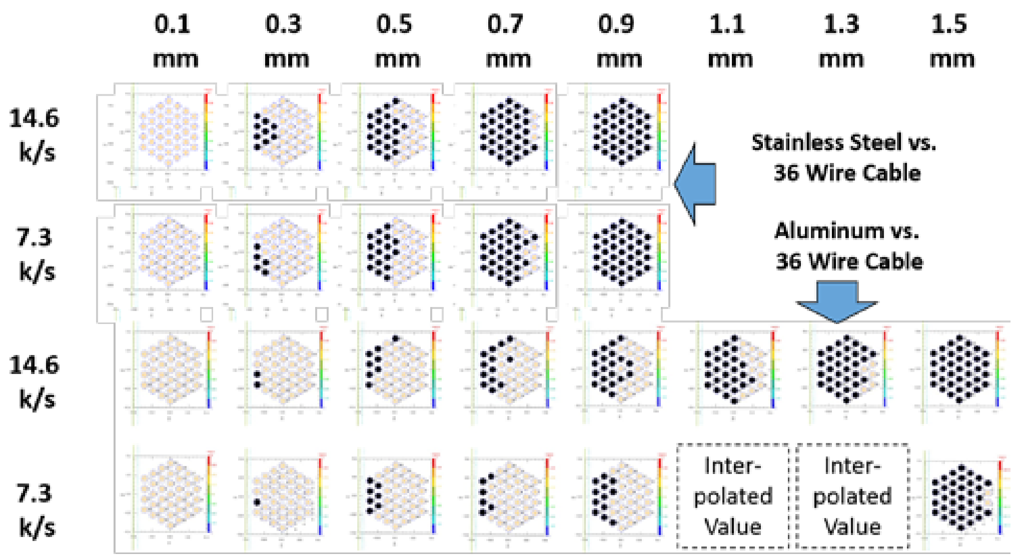


Figure 3. Number of Wires Cut in 36-Wire Bundle for Given Combinations of Orbital Debris Densities, Diameters and Velocities

After we predicted the number of penetrated wires using the SPH hydrocode (and associated it with a probability of cable failure, as shown in Figure 4), we determined the probability of those conditions occurring on orbit using NASA's ORDEM 3.0 (Matney et al. 2014). Larger particles are less likely than small particles to impact a given area on orbit, and we can associate a probability with each size that

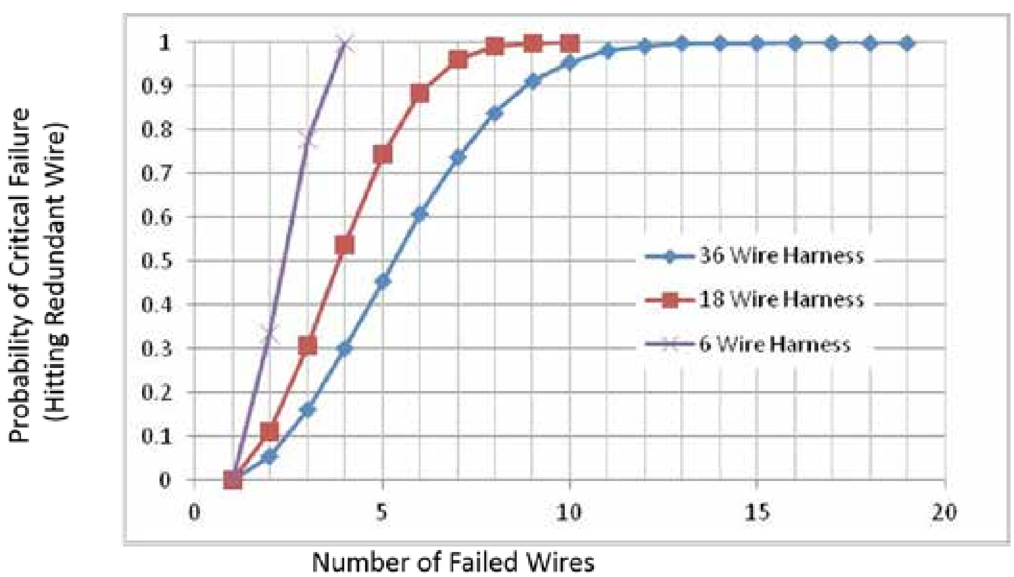
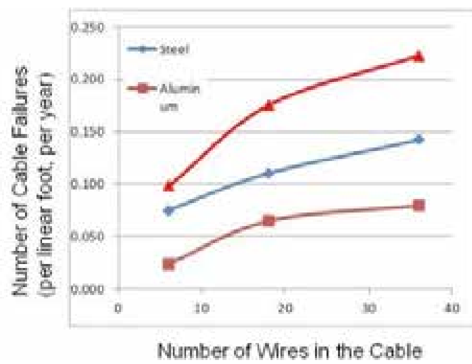


Figure 4. Probability of Critical Failure vs. Wire Harness Size Given Randomly Placed Redundant Wire Failure

causes failure. In this case, we developed an Excel spreadsheet that interpolated the size and velocity of steel and aluminum particles causing from 1 to 36 wire failures based on the hydrocode results and then calculated the likelihood of those particle combinations impacting the cables for a 1-foot length of cable in a year. Figure 5 shows the expected probability of orbital-debris-induced cable failure for a one year exposure of a 1-foot length of 6-, 18-, and 36-strand cables, where every strand within a cable carries a critical function and has a redundant wire somewhere in the cable carrying the same critical function. However, real spacecraft cables are often bundled together, shadowing one another, and are located in orientations and locations where other spacecraft components shadow them. They also often carry less than critical functions. Table 1 shows that considering these potential effects of shadowing, position, and criticality can lower the likelihood of critical cable failure (for the 8-foot cable example) by a factor of 20. However, even this risk is too high, considering that hundreds of feet of cabling would be exposed to the orbital debris environment.



Bundle Size	Steel	Aluminum	Total
6	0.075	0.024	0.099
18	0.111	0.065	0.176
36	0.143	0.080	0.223

Figure 5. Cumulative Number of Cable Failures for Three Cable Sizes (1-Foot Length, Zenith/Nadir Orientation, 1-Year Exposure)

Table 1. Effect of Shadowing and Reduced Criticality on a Typical 8-Foot Cable

Cable	Length (ft)	Baseline n Fails	Portside Shadowing	Front (0 deg) Shadowing	45 deg Shadowing	Bundle Shadowing	Criticality	Realistic n fails
1	2	0.446	0.5	0.46	0.84	1	0.5	0.043084
2	2	0.446	0.5	0.46	0.84	0	0.5	0
3	2	0.446	0.5	0.46	0.84	1	0.5	0.043084
4	2	0.446	0.5	0.46	0.84	0	0.5	0
	Baseline n fails	1.784			More realistic n fails in 8 ft			0.086
	Failure per foot	0.223				Failures per foot		0.011
					Unshadowed baseline vs Realistic			20.7

TASK 2: EVALUATING AN ENHANCED MICROMETEOROID AND ORBITAL DEBRIS SHIELD

Based in part on the high computed risk of a critical wire bundle failure from the generic approach, the program decided to implement an enhanced micrometeoroid and orbital debris (MMOD) protection design consisting of betacloth-reinforced MLI suspended at a 5-centimeter standoff over a 7-layer betacloth and Kevlar blanket, draped over the exposed wire bundles, as shown in Figure 6. It is noteworthy that 99.5 percent of orbital debris approaches from within the X-Y (orbital) plane and that orbital debris approaching from the Y axis (from the "front" as viewed by the spacecraft) makes up nearly 50 percent of this flux. This threat would impact the deck at 14.6 kilometers per second (km/sec) and impact the blanket at 75 degrees obliquity, relative to the exposed wires on the zenith deck. The ultimate objective was to develop a design that prevented penetration of the blanket from 3mm aluminum spheres and 2mm steel spheres considering these "worst case" impact conditions shown in Figure 6.

As shown in Figure 7, SPHC analyses showed that the enhanced shield was capable of preventing penetration of a 3mm aluminum and 2.12mm orbital debris particle at the stated conditions. By preventing penetration of the blanket from these particle sizes, the wires are automatically protected to at least that degree.

Once we determined the ballistic limit of the blanket for the worst case orientation (and highest orbital debris flux), we calculated the exposed area for the blanket (and wiring beneath it) using the configuration shown in Figure 8. The JPSS-1 spacecraft features radiators on the "sides" of the spacecraft that block much of the orbital debris from approaching the spacecraft from angles at 15 degrees or more from the velocity vector. A cardboard model and a simple digital camera were used to estimate the amount of shadowing achieved on the surface of the spacecraft.

Table 2 shows that there is only a 5.3 percent probability that one or more orbital debris penetrations of the enhanced shield over the zenith deck wiring will occur in the expected 7-year operation of the JPSS-1 spacecraft. Most of this risk results from penetration by stainless steel particles, due to their lower ballistic limit and higher flux on the enhanced wiring shield.

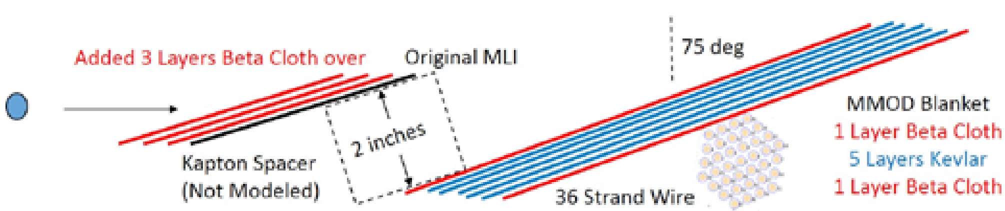


Figure 6. Enhanced Shield Configuration For Defeat of 3mm Aluminum Orbital Debris Particles

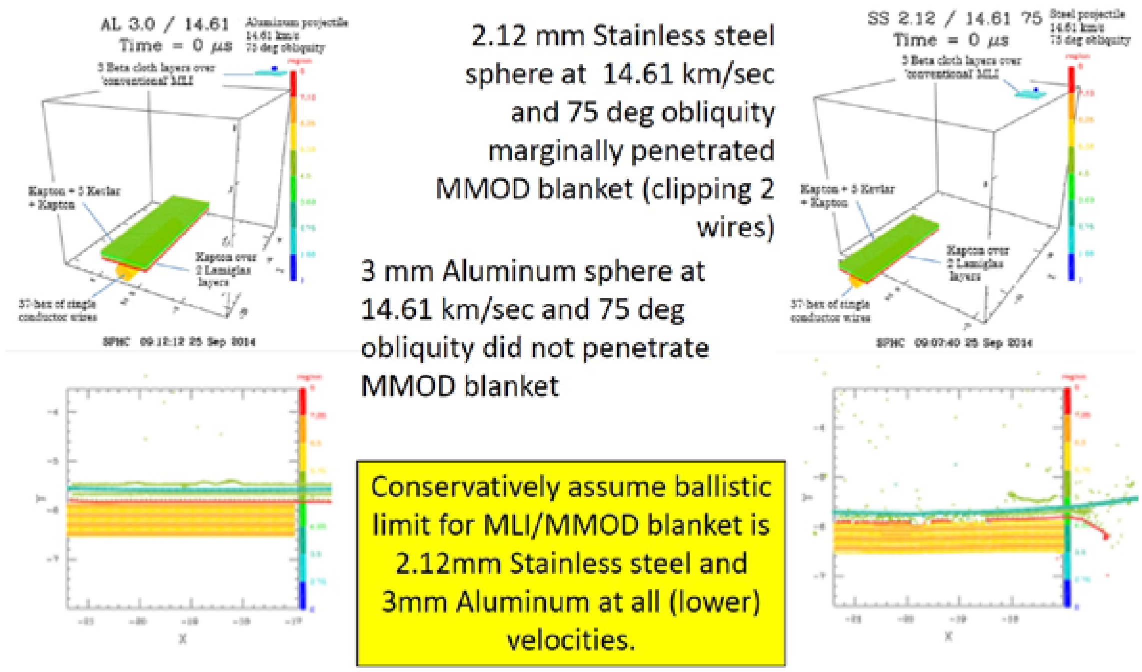
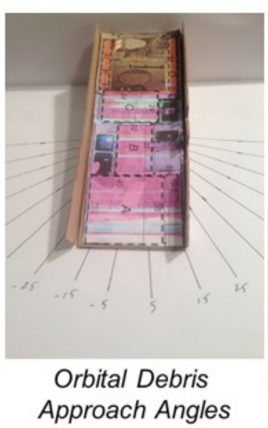
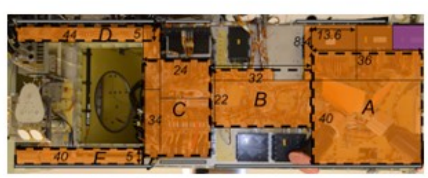


Figure 7. Hydrocode Evaluation of Enhanced MMOD Shield for Steel and Aluminum Orbital Debris





		Exposed Area Including Shadowing by Approach Direction (m²)									
Region	Surface Area	0 deg	5	15	25	35	45	55	65	75	85
A	0.930	0.241	0.239603	0.233331	0.219177	0.098527	0.042508	0.013805	0.005134	0.000639	0.000218
B	0.454	0.118	0.117139	0.114073	0.053577	0	0	0	0	0	0
C	0.527	0.137	0.135775	0.105777	0	0	0	0	0	0	0
D	0.142	0.037	0.036606	0.035648	0	0	0	0	0	0	0
E	0.129	0.033	0.033278	0	0	0	0	0	0	0	0
	Obliquity	75	75.1	75.5	76.4	77.8	79.5	81.5	83.7	86.1	88.7
	Total Area	0.57	0.56	0.49	0.27	0.10	0.04	0.01	0.01	0.00	0.00

Figure 8. Exposed Areas of Wire Harness by Approach Angle

Table 2. Total Estimated Risk of Blanket Penetration by Steel and Aluminum Orbital Debris Particles

Steel risk with shadowing

		Steel		7 years
Approach	BL for N	Pen Flx	Area	N pens
5	2.120	0.003448	0.562	0.013563491
15	2.120	0.001757	0.488	0.006000823
25	2.120	0.000942	0.272	0.001792875
35	2.120	0.000688	0.098	0.000472185
45	2.120	0.000549	0.042	0.000161411
55	2.120	0.000484	0.013	4.40532E-05
65	2.120	0.000462	0.005	1.61581E-05
75	2.120	0.000471	0.0006	1.97961E-06
85	2.120	9.55E-05	0.0002	1.33696E-07
		Total Port		0.0221
		Total Stbd		0.0221
		Total		**0.0441**
		Ppen		**0.0431**

Aluminum risk with shadowing

		Aluminum		7 years
Approach	BL for N	Pen Flx	Area	N pens
5	3.000	0.000678	0.562	0.002668771
15	3.00	0.000503	0.488	0.001718317
25	3.000	0.000259	0.272	0.000493157
35	3.000	0.000184	0.098	0.000126244
45	3.000	0.000149	0.042	4.38661E-05
55	3.000	0.000129	0.013	1.17334E-05
65	3.000	0.000116	0.005	4.07175E-06
75	3.000	0.000114	0.0006	4.80279E-07
85	3.000	6.57E-05	0.0002	9.19177E-08
		Total Port		0.0051
		Total Stbd		0.0051
		Total		**0.0101**
		Ppen		**0.0101**

Total Risk ~ 5.3% probability of 1 or more MMOD blanket penetrations in 7 years.

SUMMARY AND CONCLUSIONS

Two approaches were pursued to evaluate the risk from orbital debris penetration of exposed JPSS wiring. In the first case, a "generic" approach considering normal impact of the baseline MLI over wires resulted in an evaluation of wire damage that was very conservative, in that it did not initially consider the effects of obliquity or shadowing by other spacecraft components and adjoining wiring and could not be sufficiently refined to account for the exact wiring bundle design, including redundancy. This resulted in an unacceptably high risk, according to JPSS program management.

In the second case, an enhanced orbital debris shield was added over the wires and evaluated to provide less than a 5.3 percent probability of blanket penetration in 7 years. However, shield penetration should not be equated to critical wire failure. The figure of 5.3 percent "risk" of shield penetration is an upper bound for critical wire failure risk, for the following reasons:

- Penetration of the wires below the blanket would require a larger (and less likely) orbital debris particle, thus lowering computed risk compared to the blanket itself.
- Actual wire coverage is less than the coverage of the MMOD blanket (lowering critical wire risk).
- There is a higher ballistic limit of the shield at other approach angles since that debris approaches at a lower velocity.

- Not every wire is critical, and many wires are redundant.
- Many of the critical wires are placed below other wires, so more shadowing is likely than was accounted for in this assessment.

Considering these factors, the probability of critical wire failure on the zenith deck could be well beneath 1 percent.

EPILOG

The NASA-IDA team was awarded the NASA Group Achievement award, chosen by the NESC Director "in recognition of outstanding accomplishment through the coordination of individual efforts that have contributed substantially to the success of NESC's mission."

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Orbital Debris Wire Harness Failure Assessment for the Joint Polar Satellite System

http://www.sciencedirect.com/science/article/pii/S1877705815007584

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AGILITY QUOTIENT (AQ)

David Alberts

How can we measure an entity's probability of success without specifying the nature of the mission or the circumstances under which it will be conducted?

Progress in designing and developing more agile entities will depend on our ability to observe appropriate behaviors and outcomes, associate these behaviors and outcomes with entity characteristics, and determine the amount of agility required.

The concept of agility is increasingly recognized as a "must-have" capability for individuals and organizations and for the systems that support them. Enterprises are called upon to perform successfully—if not thrive—in environments that are ever more complex and dynamic. Because of the complexity and dynamics involved, theoretical planning assumptions "to survive first contact with the enemy" are insufficient. The capability to effect, cope with, and/or exploit unexpected circumstances and changes successfully is necessary. This capability has been defined as *agility* (NATO 2013).

Commanders and managers at all levels are faced with the challenge of ensuring that their organizations will be agile, while system designers and developers need to ensure that systems that can adequately support users under these conditions. To know whether these commanders and managers have the requisite amount of agility to face an uncertain future, two questions have to be answered:

- How can potential agility be measured?
- What is the amount of agility required?

THE CONCEPT OF AGILITY

The definition of agility and its six enablers—responsiveness, versatility, flexibility, resilience, adaptiveness, and innovativeness—has been discussed and explored in North Atlantic Treaty Organization (NATO) and U.S. Department of Defense Command and Control Research Program (DoD CCRP) publications (International Command and Control Institute n.d.). These publications provide a conceptual framework that can be employed to find an appropriate balance between and among effectiveness, efficiency, and risk and a rational basis for improving an entity's agility.[1]

Progress in designing and developing more agile entities will depend on our ability to observe appropriate behaviors and outcomes, associate these behaviors and outcomes with entity characteristics, and determine the amount of agility required. The article suggests a way forward and illustrates it in the context of command and control (C2) systems. It discusses the need to complement agility assessments based upon the observation of manifest agility with a scenario-free assessment approach that provides a measure of agility potential—an Agility Quotient (AQ).

AGILITY: KEY IDEAS

The situations that we face are inherently dynamic. Initial solutions—even if these solutions are effective—will become less effective over time. Plans will be, at best, short lived because no matter how much we invest in information and analysis to reduce uncertainly, a significant amount of residual uncertainty will remain. We will always have to address unexpected and unanticipated events and circumstances. Agility is the only way to meet the challenges of complexity and dynamics that does not require ignoring problem difficulty to find a solution (Alberts 2011).

While the definition of agility used here is widely accepted within the C2 research community, different communities define agility in different ways and/or employ a variety of terms (e.g., robustness, resilience, reliability) to refer to this capability. However, these various definitions of agility, despite their differences, converge on three key ideas (Dove and LaBarge – Part 1 and Part 2 2014):

- Agility is an appropriate response to the challenges posed by complexity and dynamics and the resultant reduced ability to predict and a rise in the frequency of unanticipated events. Increased complexity is also associated with exacerbating the adverse consequences of these events, particularly since these events may trigger cascades of effects that cannot be understood or controlled adequately. This inability to understand or control events leads to an increased probability of catastrophic failure.
- Agility is inseparable from success (i.e., an appropriate measure of agility must reflect outcomes). Thus, an entity manifests agility only if and when it can seize upon an opportunity to improve performance, increase efficiency and/or reduce risk, or is able to continue to operate successfully despite being subjected to a stress that would otherwise adversely impact its ability to operate successfully.
- Agility is not a passive concept but is one that includes anticipatory and proactive behaviors.

[1] *Entity* is used here to refer to the unit of analysis, whether it is an individual, a group of individuals, a formal organization, a coalition, a process, a policy, or a system.

OBSERVING AND MEASURING AGILITY

The manifestation of agility requires a successful outcome. Depending on the nature of the entity, success will be determined by some combination of performance or effectiveness, costs, and risks. While success or a lack thereof can usually be easily observed, the reasons are often less apparent. Clearly, one can conceive of numerous reasons why an entity might be successful in spite of itself, its capabilities, and even its lack of agility. Thus, success alone should not be equated with agility. While it is difficult—if not impossible—in real-world situations to establish a cause-effect relationship between a successful outcome and the "exercise of agility," it is possible to observe specific enablers of agility (or a lack thereof) in entity behaviors and employ measures of the degree to which these enablers are present.

The following enablers of agility have been identified and defined (NATO 2013):

- Responsiveness
- Versatility
- Flexibility
- Resilience
- Adaptiveness
- Innovativeness

The manifestation of agility and its impacts can be directly observed and measured but only when circumstances require agility and when the entity is able to respond appropriately. When an entity does not possess adequate agility, this lack of agility can also be observed.

A metric can be derived from these observations. For example, a measure of potential agility based upon experience and analysis is the probability that an entity has manifested agility when required. Calculating this probability is a three-step process:

- The first step involves the construction of an Endeavor Space, a space that includes the population of missions and circumstances. This construct provides the set of missions and circumstances whose characteristics need to be analyzed to determine whether the entity can successfully operate in different parts of the Endeavor Space (Alberts 2011). A more sophisticated analysis could estimate the conditional probability of success.
- The second step is to project whether the entity can successfully operate in each part of the space.
- The third step is to sum the outcomes across the Endeavor Space.

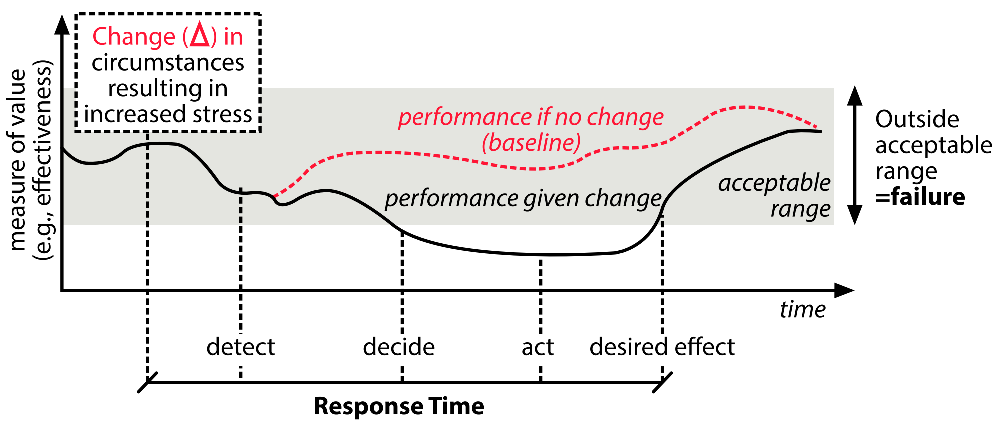
AGILITY ADVANTAGE

Success and failure have associated costs. One way to determine the value of agility is to take into consideration the amount of time that an entity could not perform acceptably and the magnitude of the performance shortfall, as is depicted in Figure 1.

Figure 1 provides a response timeline that, if improved, could (1) reduce the amount of time an entity failed to perform within acceptable bounds or (2) decrease the amount of the performance gap. While Figure 1 helps us determine the opportunity loss incurred by a lack of agility, we need more information to determine what is needed to improve agility.

AGILITY ATTRIBUTION AND MEASUREMENT

The SAS-085 case studies were able to identify the presence or absence of agility enablers and associate these observations with manifest agility (NATO 2013).[2] While identifying instances in which agility was not manifested can identify problems areas on which to work, instances of manifest agility should not be considered to be proof of adequate agility because the sample of stresses and conditions considered is extremely small and not necessarily representative of future conditions. Fortunately, we do not need to limit our assessment of agility to observations of an entity in operation. One approach augments real-world observations by putting an entity (or a simulated entity) in a controllable/ instrumented environment, creating possible futures, and performing observations under a variety of scenarios without waiting for these scenarios to occur in the real world. The set of scenarios that is used, plus those scenarios that are thought to be "lesser included cases," could form the basis for an Endeavor Space. This space can be used to calculate an absolute measure of agility, a probability of success, or a relative measure that simply compares two entities or instantiations to the same standard.



Source: Alberts 2011.

Figure 1. Observing Entity Performance

[2] SAS-085 Case Study methodology and results can be found in Chapter 7 and Appendix B of NATO (2013).

Scenario-based approaches can result in a biased measure of potential agility. Their accuracy depends upon the number and nature of the scenarios used to create the Endeavor Space and whether this space adequately encompasses future situations. Some analysts focus on the "most likely" situations and stresses, while other analysts focus on the most stressing circumstances. In either case, it seems inevitable—and the evidence suggests—that the set of scenarios employed will be constrained by preconceived notions, groupthink, and biases.

This situation does not imply that we should abandon a scenario-based approach; rather, it suggests that we should be careful to employ scenarios in a thoughtful way. Given these inherent limitations, the development of a measure of an entity's potential agility (i.e., AQ [Agility Quotient]), patterned after the Intelligence Quotient (IQ), makes sense. IQ tests seek to measure cognitive capabilities. These tests are attempts to measure fundamental attributes or capabilities of individuals that enable them to learn and apply knowledge. Since inception of these tests in the early 1900s, their developers have recognized that intelligence is a concept that is too encompassing to be measured in a scalar metric (Cherry 2016). Furthermore, a host of factors besides genetics could influence intelligence and, along with other factors, could bias test results. We need to keep this in mind as we try to develop and employ AQ tests.

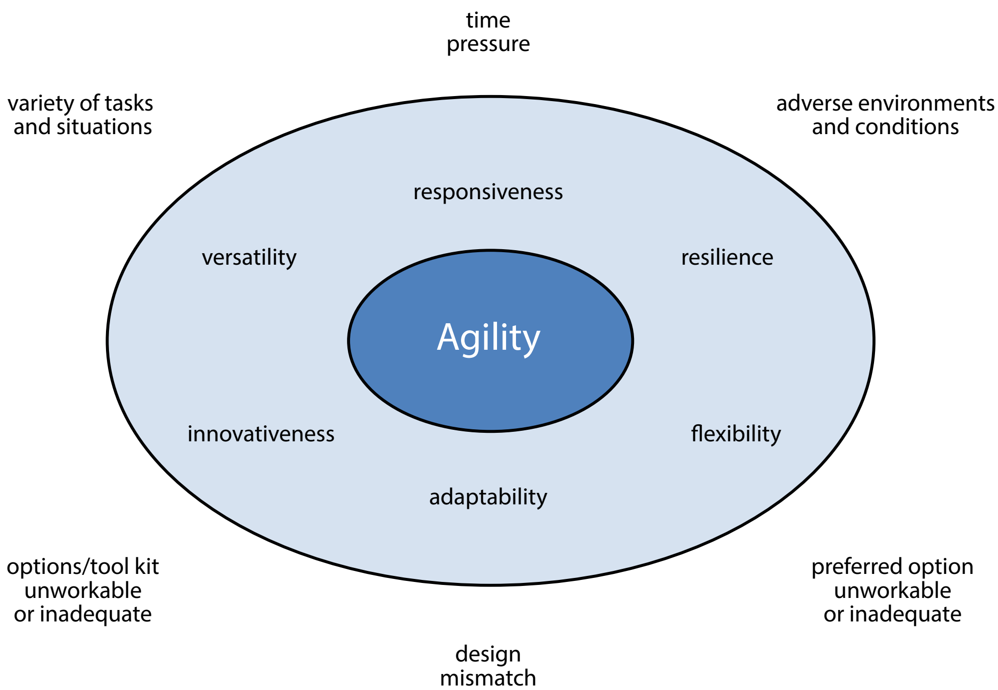
It seems reasonable to begin by building upon the enablers of agility that have, to some extent, been validated in case studies and experiments.

Figure 2 depicts the enablers of agility in the context of the characteristics that make tasks difficult and/or conditions that stress an entity:

- Responsiveness is required to accommodate time pressures.
- Resilience is required to recover from damage or degradation.
- Flexibility is needed when one way of accomplishing something does not work.
- Versatility is needed when an entity is used for multiple purposes.
- Innovativeness is required when existing ways and means are not adequate for the task and circumstances.
- Adaptability is required when, to succeed, the entity needs to change itself. The ability of an entity to change itself includes but is not limited to being able to adopt different approaches to C2 (Alberts 2011).

A MODEL OF C2 AGILITY POTENTIAL: C2 AQ

The development of a model of C2 AQ is used to illustrate an approach to ascertaining an entity's potential agility. C2 Agility is about ensuring that an appropriate approach to C2 is being employed. There are many ways to accomplish the functions we associate with



Source: Alberts and Hayes 2006.

Figure 2. Enablers of Agility

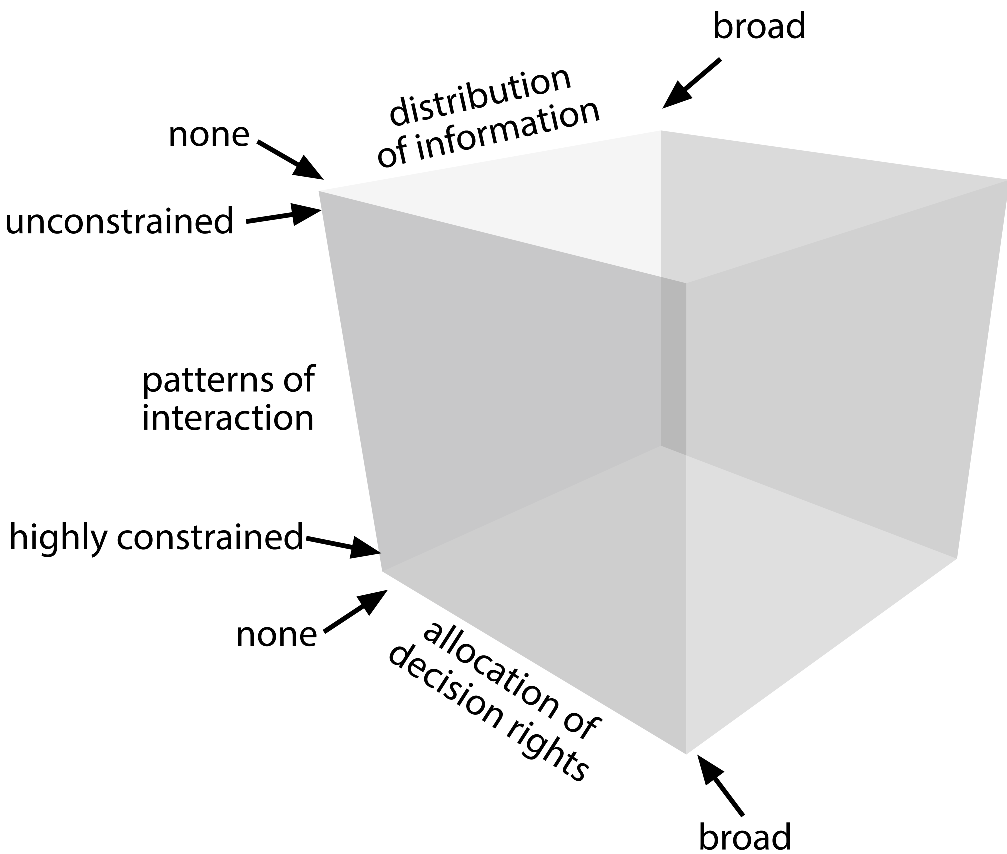
C2 with different approaches corresponding to different regions in the C2 Approach Space (see Figure 3)

Experience, case studies, and experiments have yielded many C2 Agility-related findings and have explored the following hypotheses to be considered in a model of C2 AQ:

- There is no "one-size-fits-all" approach to C2 that works well for all missions and circumstances.
- Network-enabled approaches to C2 are more agile than others.
- Balanced approaches to C2 are more agile.
- The "selected" approach to C2 may not be the one that is actually being implemented.
- Being able to adopt more than one approach improves agility (C2 maneuver).
- Agile individuals, processes, policies, and systems—each and in combination—improve the agility of a given C2 Approach and the ability to appropriately maneuver in the C2 Approach Space.

To the extent that these hypotheses have merit, an entity's C2 Agility is a function of the following:

- Number of different C2 approaches available
- Agility of each of these C2 approaches
- Ability to maneuver appropriately in the C2 Approach Space.



Source: Alberts 2011

Figure 3. The C2 Approach Space

The C2 Agility-related lessons learned suggest a number of questions (see Figure 4), the answers to which would provide some indication as to an entity's C2 AQ and point to some observables that could be used to construct a model of C2 AQ. These questions are but a small sample of those questions that are suggested by these and other lessons learned and reported on in the NATO Research Group SAS-085's Final Report on C2 Agility (NATO 2013).

C2 Agility depends to a significant extent on the agility of the systems that support C2. More agile systems are less likely to impose constraints on an entity's choice of C2 Approach. Thus, a holistic approach to C2 AQ should be taken—one that includes a consideration of the agility of the communications and information systems that support C2 processes and the agility of the processes themselves.

A number of systems engineering principles are thought, if followed, to produce more agile systems. These principles are related to reusability, reconfigurability, and scalability. These means of enabling agility, as well as others that may be identified, can provide the basis for the development of agility "markers"—variables that measure the degree to which a means has been achieved. These markers can serve as indicators of potential agility and can be integrated into an agility value proposition. Systematic experimentation is needed to validate these markers and refine our understanding of the agility value chain. The aim of a model of potential agility is to integrate all of these means and markers into a value proposition—one that enables "designers" of organizations and systems (e.g., commanders, managers, and engineers) to understand better how they can enhance an entity's potential agility and to do so efficiently.

- **What is the most network-enabled approach that can be adopted?**
- **How many different approaches to C2 can be adopted?**
- **How is the approach to C2 initially determined?**
- **Is the appropriateness of the C2 Approach periodically assessed?**
- **Is the way C2 is currently being approached monitored?**
- **Are there processes in place to ensure that the C2 Approach is balanced?**
- **Is the state (performance) of supporting systems monitored?**
- **How agile are individuals, processes, and supporting systems?**

Figure 4. Agility-related Questions

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Systems Agility Quotient (AQ)

http://onlinelibrary.wiley.com/doi/10.1002/inst.201417210/abstract

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