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Statistical Risk Estimation for Communication System Design: Results of the HETE-2 Test Case

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ABSTRACT. — The Statistical Risk Estimation (SRE) technique described in this article is a methodology to quantify the likelihood that the major design drivers of mass and power of a space system meet the spacecraft and mission requirements and constraints through the design and development lifecycle. The SRE approach addresses the long-standing challenges of small sample size and unclear evaluation path of a space system, and uses a combination of historical data and expert opinions to estimate risk. Although the methodology is applicable to the entire spacecraft, this article is focused on a specific subsystem: the communication subsystem. Using this approach, the communication system designers will be able to evaluate and to compare different communication architectures in a risk trade-off perspective. SRE was introduced in two previous papers. This article aims to present additional results of the methodology by adding a new test case from a university mission, the High-Energy Transient Experiment (HETE)-2. The results illustrate the application of SRE to estimate the risks of exceeding constraints in mass and power, hence providing crucial risk information to support a project's decision on requirements rescope and/or system redesign.

I. Introduction

The Statistical Risk Estimation (SRE) technique described in this article is a methodology to quantify the likelihood that the major design drivers of mass and power of a space system meet the spacecraft and mission requirements and constraints through the design and development lifecycle.

The methodology focuses on the problem that, during different design phases, engineers are compelled to estimate the values for mass and power at the component level and at the subsystem level, and these values inevitably fluctuate over time. This problem is crucial in spacecraft design as each mission is subjected to constraints in the maximum launch mass and power of the spacecraft.

The SRE technique developed in this research enables engineers to evaluate the design risk of different architecture options, to perform a risk-performance trade-off, and to make

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opportune design adjustments during the early system design phases — from preliminary design review (PDR) through critical design review (CDR). The statistical analysis framework uses a combination of two information sources: historical data and expert opinion. The information conveyed by data and by experts is elaborated through a cluster of different statistical techniques, with the objective of calculating the overall design risk.

The following is a summary of prior work that addresses the problem of design risk. SRE was introduced in [1]. In [2], the results of a study case developed using a university mission, Cathode/Anode Satellite Thruster for Orbital Repositioning (CASTOR), were presented. Cortellessa [3] categorized the different possible design risks. Meshkat [4] analyzed design risk and described different cases in which she observed "significant deviations in mass and power" from the initial system design to the final system design. Barrientos [5] explored the causes of design risks, and focused on the lack of human interaction between engineers. Oberkampf [6] analyzed the causes of risks, while Asnar [7] developed qualitative risk analysis techniques to deal with the problem of selecting across design alternatives. A more quantitative approach to design risk can be found in the works of M. Fuchs and A. Neumaier [8,9,10]. They described a statistical approach based on the creation of an n-dimensional cloud of uncertainties in which the different architectural solutions lie. This methodology represents the first attempt to statistically model the lack of knowledge in the space system design process. However, this methodology is based on expert opinion only, while our approach uses a combination of measured data and experts.

Previous work done by the authors includes the development of an approach to model expert opinion [11], the creation of the statistical methodology with preliminary results [1], the application of the statistical methodology to a satellite mission developed at the Massachusetts Institute of Technology (MIT), the CASTOR satellite [2], and the development of an optimization framework [12].

The article is organized as follows: Section II recalls the main aspects of the SRE methodology, the statistics used, and the results obtained in the case of the CASTOR test case. Section III describes the High-Energy Transient Experiment (HETE)-2 test case and the results of the SRE methodology developed, and Section IV presents conclusions and suggestions for future work.

II. Statistical Risk Estimation Technique

A. Overview

The SRE technique provides a statistical quantification of the risk for a system to exceed constraints in mass and power over the temporal evolution of the design. The methodology is explained in detail in [2]. A summary of the main aspects of the approach applied to the communication system is presented in this section. A graphical summary of the methodology is shown in Figure 1.

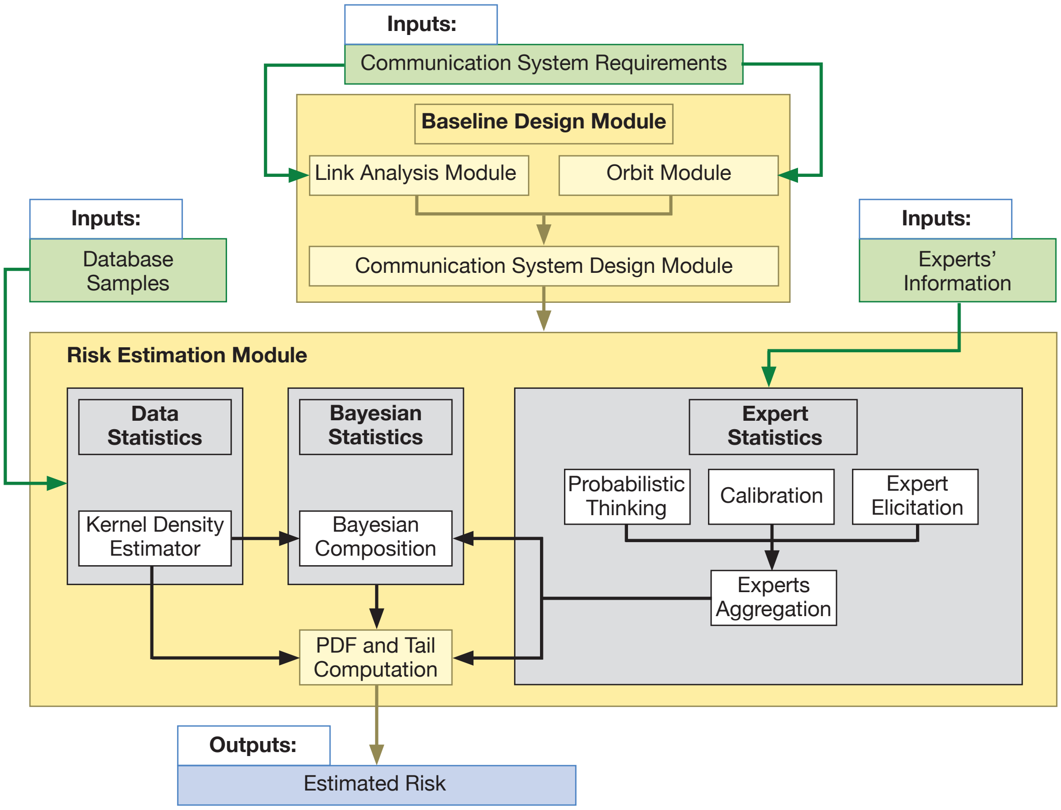

Figure 1. Summary of the SRE methodology.

The methodology starts with a baseline design, which is generally the design at PDR or any initial design of a communication system. The design is described in terms of the most important parameters for a communication system: effective isotropic radiated power (EIRP), data rate, orbit, and mass and power consumption for each component. The initial PDR design can be generated by the baseline tool of the SRE model, as described in [13]. However, in cases in which the design is already available, this part of the model can be skipped.

After defining the design, the risk of exceeding specific metrics in mass and power needs to be computed. The risk probability density functions are elaborated using data and expert opinion, and they are described in the next subsection.

Finally, when the risk is computed, the model produces an estimation of the risk of exceeding a specific constraint in mass and power for each element of the design. This information can be used also to compare different possible communication architectures on the basis of risk, which can also be useful in the case of trade space analysis and optimization, as described in [12].

B. Statistics

Three statistics are used to quantify risks:

- *Data statistics*. Data statistics use measured samples to construct the probability distributions of the mass and power of a component. Each sample is normalized into a coefficient that represents a relation between two parameters. For example, instead of collecting the mass values of the antennas for all the possible gains, the mass data collected are converted to mass per unit of gain. The kernel density estimator is used as the method to generate the probability density functions. More information on the statistics is discussed in [2] and [1].
- *Expert statistics*. A three-part methodology is used to calibrate and elicit expert opinions. Details on the methodology can be found in [11]. The methodology allows the statistician to properly weight experts' opinions on the basis of their biases and calibration.
- *Quasi-Bayesian statistics*. This is a composition of the previous two statistics performed according to a quasi-Bayesian rule for which the data statistic is treated as the prior distribution and the expert statistic is treated as the a posteriori likelihood function.

The test case analysis will show advantages and disadvantages of each of the statistics and describe why they provide complementary information.

Risk estimation is expressed in terms of tail functions, defined as the complement of the cumulative distribution function (CDF). For example, the tail for probability density function $f(x)$ computed starting from value M (which represents a design constraint for which the risk of exceeding that value is computed), is

$$\int_{M}^{\infty} f(x)\,dx. \tag{1}$$

C. CASTOR Test Case Results

The SRE methodology has been successfully applied to the CASTOR test case, as described in [2]. In that case, a simple S-band communication system composed of three identical antennas and two identical transceivers was studied. Results showed that the model was able to identify cases of overestimation or underestimation with respect to the final values of mass and power consumption for a component. The study results can be summarized as follows:

- *Data statistics* are useful to compute an estimate of the final value of mass and power of a component. However, the tail functions computed through data statistics present heavy tails that generate very cautious estimates of risk. As a consequence, an engineer who uses only data statistics to perform the estimation will be able to assess properly the likely value of mass and power consumption of the component by looking at the peaks of the probability density functions, but the risk estimation for the component will tend to be conservative.
- *Expert statistics* sometimes tend to overestimate the mass and power consumption. However, the expert's confidence helps to limit the variance (or spread) of the distribution, thus reducing the required margin to counteract the design risk. Hence, an engineer who uses expert statistics will be able to estimate properly the risk and the contingency, while

the assessment of the likely value of mass and power consumption will generally suffer from some overestimation.

- *Quasi-Bayesian statistics* combine both sources of information in a mathematically tractable manner, making it a good compromise among the solutions.

III. HETE Test Case

This section describes the application of the SRE methodology to the HETE-2 test case. First, the mission and the communication system developed are presented, followed by a description of the results of the application of the SRE methodology.

A. Mission Description

The HETE-2 [14] mission was an international mission principally developed by MIT. HETE-2 was designed to detect cosmic gamma-ray bursts (GRBs) to determine their origin and nature. The satellite had three instruments: a set of wide-field gamma-ray spectrometers, a wide-field X-ray monitor, and a set of soft X-ray cameras. The goal of the mission was to scan the sky, to identify GRBs, to establish precise locations, and to transmit coordinates in near real time.

The spacecraft was a rectangular cube (100 × 50 × 50 cm) with four deployed solar panels. The bottom section of the spacecraft contained the power, communications, and attitude control and the upper section contained the scientific instruments.

The communication system [14] used S-band for uplink (2.092 GHz) and downlink (2.272 GHz). The system included a transceiver and five patch antennas installed in different locations on the spacecraft. A GPS channel was also available, composed of an antenna and a GPS receiver. Finally, a VHF downlink (137.9622 MHz) was used for real-time alerts. The ground station used was the MIT Kavli HETE network, the same as used for CASTOR. HETE-2 was successfully launched in 2000 and the mission was active until 2007.

The next two sections describe the results of applying SRE to the S-band channel and to the GPS. Due to the lack of VHF system data, the authors were not able to apply SRE to that channel.

B. Results of the SRE Methodology: S-Band Channel

The S-band system is composed of a transceiver and five patch antennas. The antennas have a gain of 5.5 dB each and the transceiver power is 8.5 W (total EIRP of the channel was 14.7 dBW). The initial mass estimate for each of the antenna was 0.2 kg at PDR, while the final value was 0.18 kg.

The risk analysis is performed using the data statistic, the expert statistic, and the quasi-Bayesian combined statistic, computed as described in [2]. The probability density functions and tail functions for HETE-2 antenna mass are shown in Figure 2 and Figure 3.

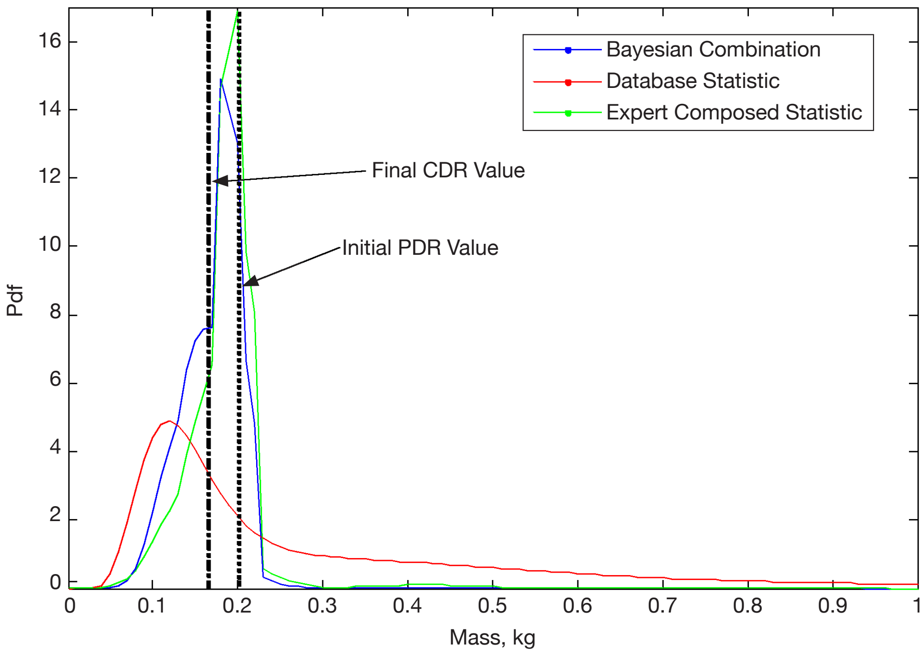

Figure 2. Probability density functions for HETE-2 antenna mass (S-band channel). The peak of the quasi-Bayesian distribution is the closest to the final CDR value.

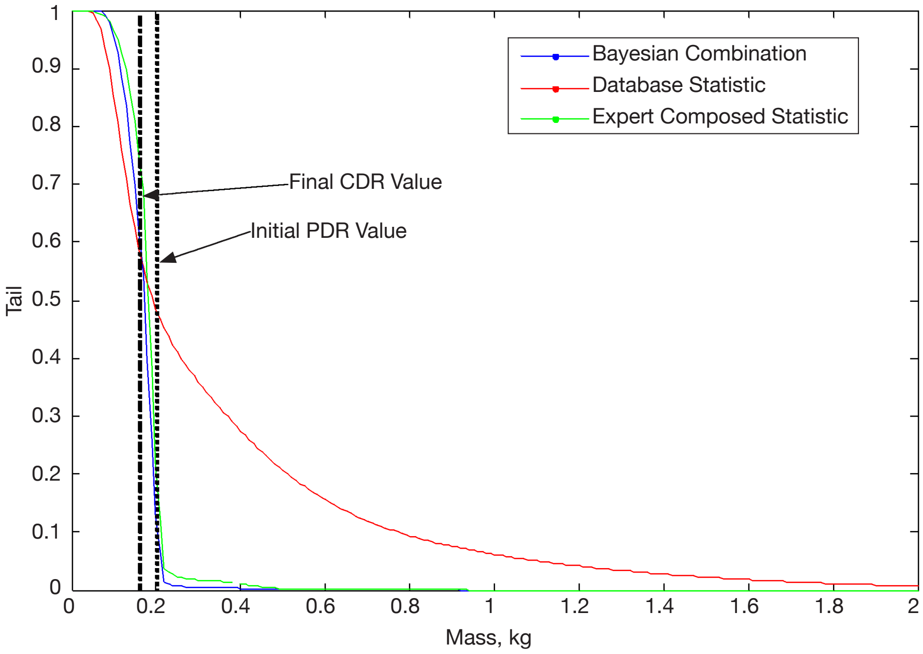

Figure 3. Tail functions for HETE-2 antenna mass (S-band channel). The experts' confidence helps to reduce the probability of exceeding the PDR value with respect to the statistic based on data.

In this case, the initial (PDR) value and the final (CDR) value are very close. Hence, it is difficult to use this test case to validate the risk model. However, it is possible to notice that the quasi-Bayesian combined probability distribution is the one that achieves the best result in this test case. Specifically, the peak of the distribution corresponds to the final (CDR) value of the mass of the component, and the tail function of the distribution (together with the one computed using expert opinion) drops very quickly to zero, showing that the PDR value is overestimated and that there is very little risk of exceeding the PDR mass value. This example (Figure 3) shows the advantage of introducing expert methodology in modeling risk estimation. In fact, the experts' confidence in the antenna's mass not exceeding 0.2 kg helps to reduce the probability of exceeding the initial estimate: a designer who might use Figure 3 to size the antenna's contingency can be very confident in allocating no more than 0.2 kg for this antenna, since the risk of exceeding this value, according to the experts, is minimal. In contrast, if only database information is available, the designer needs to allocate more mass to mitigate the risk, since the probability density, based on data, does not seem to provide a strong confidence in the design value.

In the case of the transceiver, the initial mass estimate was 1.5 kg, while the final value was 1.72 kg. The initial value for the power consumption was 30 W and the final 39.2 W.

Probability density functions and tail functions of mass fluctuations are in Figure 4 and Figure 5. For power consumption, the probability density functions and tail functions are in Figure 6 and Figure 7.

In the case of the HETE-2 transceiver's mass, all three estimates fail in identifying the final value of the mass. The peak of the distribution for the probability density generated using the data statistic (Figure 4) is far from both the initial (PDR) and final (CDR) values. Differently, the expert statistic and the quasi-Bayesian statistic are centered in the initial (PDR) value and they do not show that this value is slightly underestimated. The tail function (Figure 5) shows once again (as in the CASTOR test case) that the experts' confidence helps to reduce the probability of exceeding the initial PDR value. Also, in this case, if the designer had had to size contingency only on the basis of the data statistic, the extra mass allocated would have been much greater than the one allocated by using the expert statistic or the quasi-Bayesian statistic.

In the case of HETE-2 transceiver power consumption (Figure 6), the database statistic correctly identifies the final value of power consumption: the peak of the density is centered in the CDR value. The expert statistic and the data statistic underestimate power consumption. However, the experts' confidence reduces the uncertainty. In fact, the tail function (Figure 7) shows that the expert statistic and the quasi-Bayesian statistic may be inaccurate in predicting the peak of the density, but they provided a better identification of the risk of exceeding certain values. Specifically, tail functions computed through the expert statistic and the quasi-Bayesian statistic drop quickly just before the CDR value.

The analysis of the HETE-2 S-band channel shows that the probability density functions computed using data statistics tend to be more spread than the ones computed using expert statistics. Expert statistics and quasi-Bayesian statistics are not always able to identify the

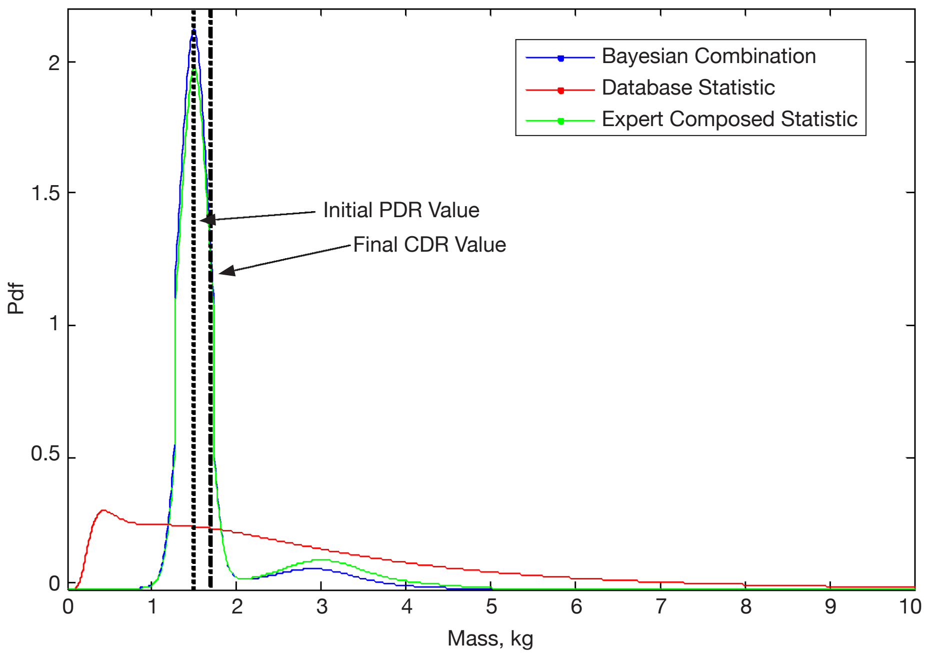

Figure 4. Probability density function for HETE-2 transceiver mass fluctuation (S-band channel). The peak values for the three densities are not centered on the final (CDR) value.

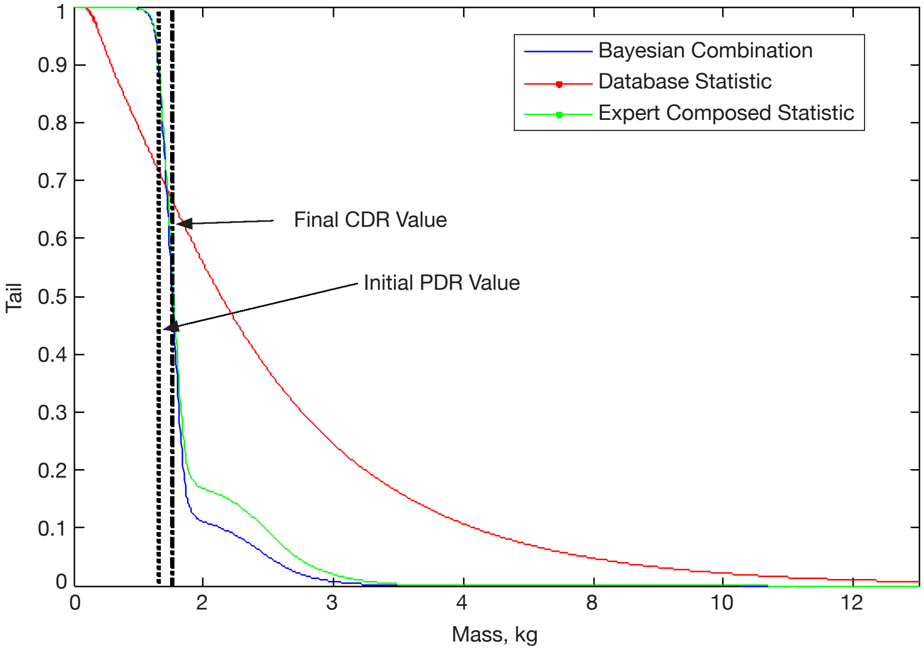

Figure 5. Tail functions for HETE-2 transceiver mass (S-band channel). The risk quantification performed with expert opinion and the quasi-Bayesian statistic allows the designer to reduce mass contingency with respect to the one performed using the data statistic.

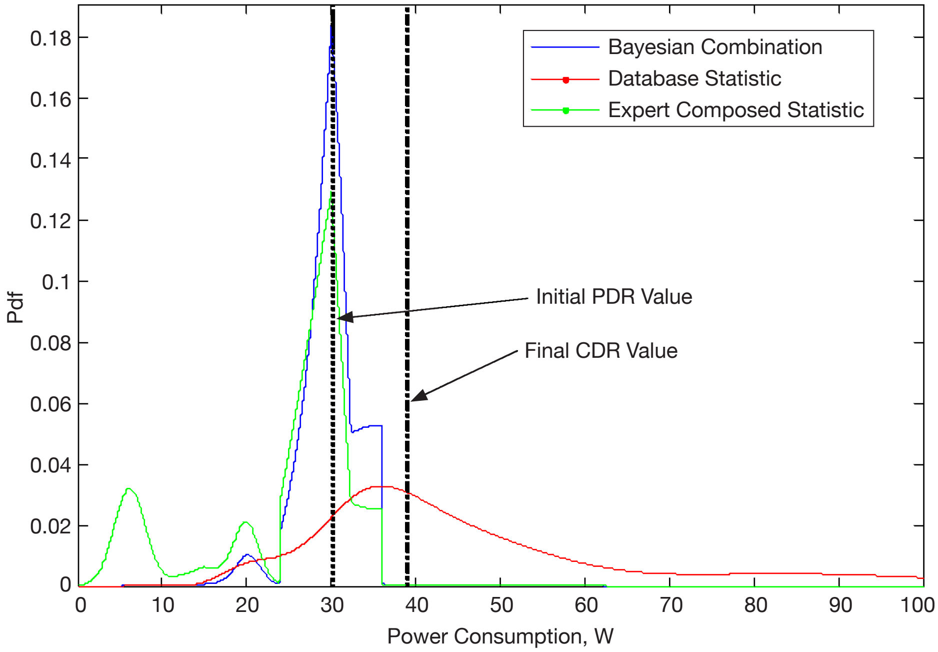

Figure 6. Probability density functions for HETE-2 transceiver power consumption (S-band channel). The peak of the data statistic is centered on the final CDR value, while expert and quasi-Bayesian statistics are closer to the initial PDR estimate.

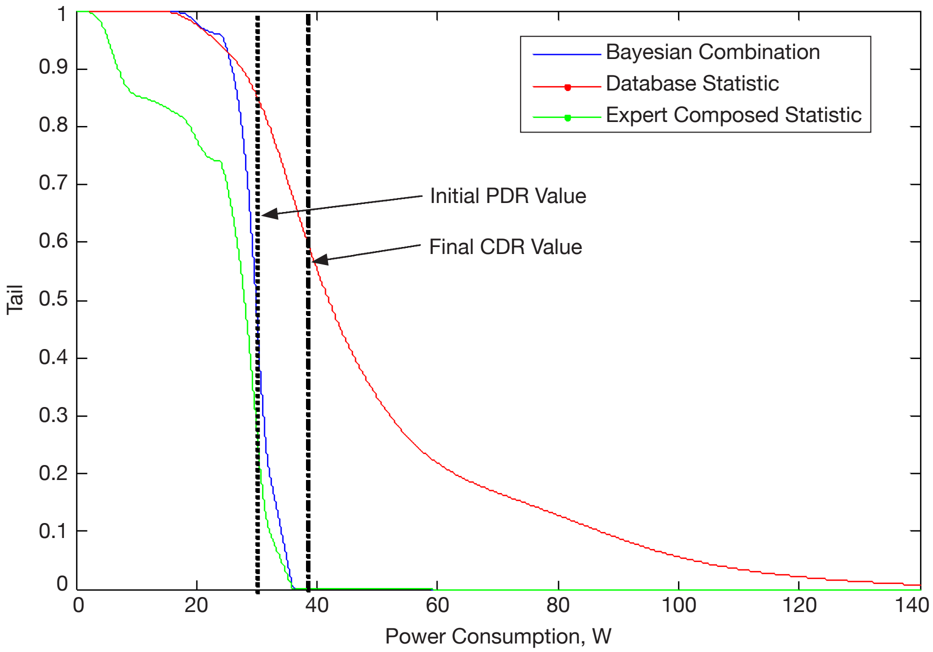

Figure 7. Power consumption tail functions for HETE-2 transceiver (S-band channel). The experts' confidence helps to reduce the risk of exceeding the initial PDR estimate and margin allocation.

final value of mass and power (the peaks of the distribution do not always align with the CDR value). However, the tail functions show that the experts' aggregated knowledge can provide a reliable risk estimation: tail functions are generally less heavy than the ones computed with data statistics at CDR value.

C. Results of the SRE Methodology: GPS System

The HETE-2 GPS channel is also analyzed. The system is composed of a 13.5-dB patch antenna and a GPS receiver. The initial value for the mass of the antenna at PDR was 0.2 kg, while the final value was 0.33 kg. The process of risk analysis using the three statistics has been applied to the GPS antenna and the results are shown in Figure 8 and Figure 9.

Also in this case, the peak of the data statistic identifies correctly the final value of the mass. On the other hand, incorporating the expert statistic helps to reduce the sizing of contingency, as shown in Figure 9.

For the GPS receiver, the initial mass was 2 kg and the final mass was 1 kg. The initial power consumption was 10 W, while the final value was 8 W. Statistics have been computed using the same techniques previously discussed. Figure 10 and Figure 11 show the probability density function and the tail function for GPS receiver mass, while Figure 12 and Figure 13 show the probability density function and the tail function for GPS receiver power consumption.

In the case of the GPS receiver, the initial mass value at PDR is overestimated. Regarding the probability density functions (Figure 10), the three statistics identify that the PDR value is excessively conservative. Moreover, the expert statistic and the quasi-Bayesian statistic present a peak value that is very close to the final CDR value. Like the case of CASTOR transceiver power consumption, the model is able to identify when an initial value of mass and power is excessively conservative or excessively risky.

Regarding the tail functions (Figure 11), the GPS receiver mass is the only case in which the data statistic exhibits a lighter tail than the expert statistic. The quasi-Bayesian statistic provides the best assessment for both density and tail function.

Regarding GPS receiver power consumption, the probability density function (Figure 12) computed using the data statistic shows that the PDR value is overestimated. Differently, the other statistics are anchored on the PDR value. Regarding tail functions (Figure 13), both the expert statistic and the data statistic exhibit heavy tails, while the quasi-Bayesian statistic obtains a slightly better result.

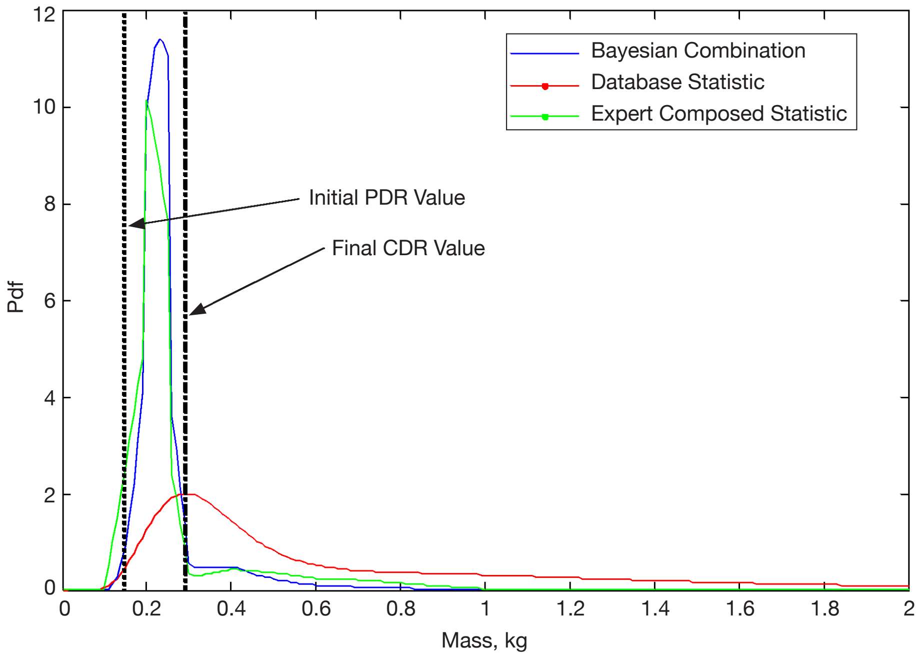

Figure 8. Probability density functions for HETE-2 antenna mass (GPS channel). The peak of the data statistic is close to the final CDR mass value.

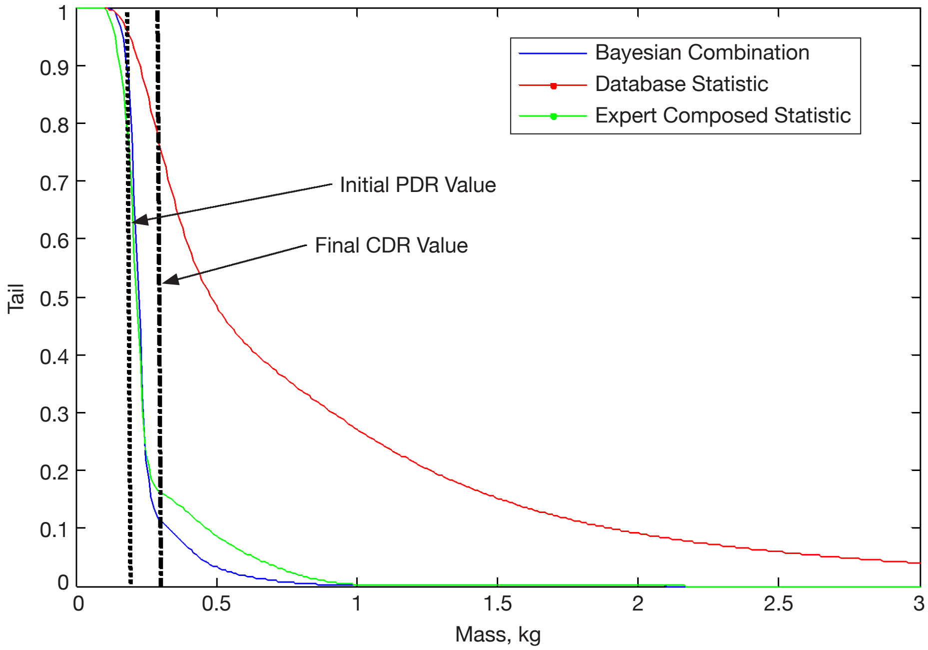

Figure 9. Tail functions for HETE-2 antenna mass (GPS channel). The experts' confidence helps to reduce contingency allocation.

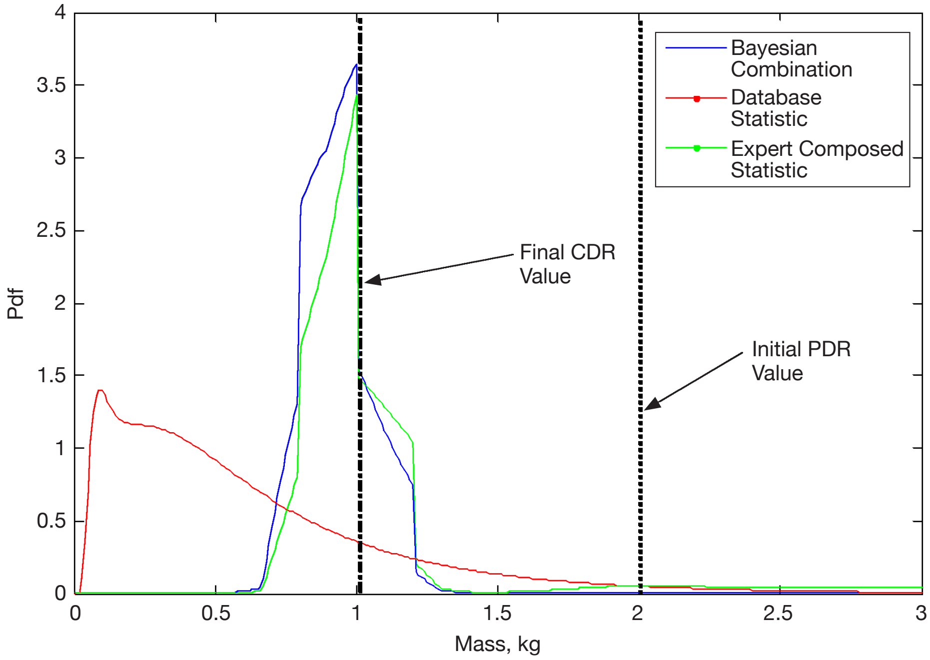

Figure 10. Probability density functions for HETE-2 GPS receiver mass. The three statistics identify the initial overestimation of the PDR value.

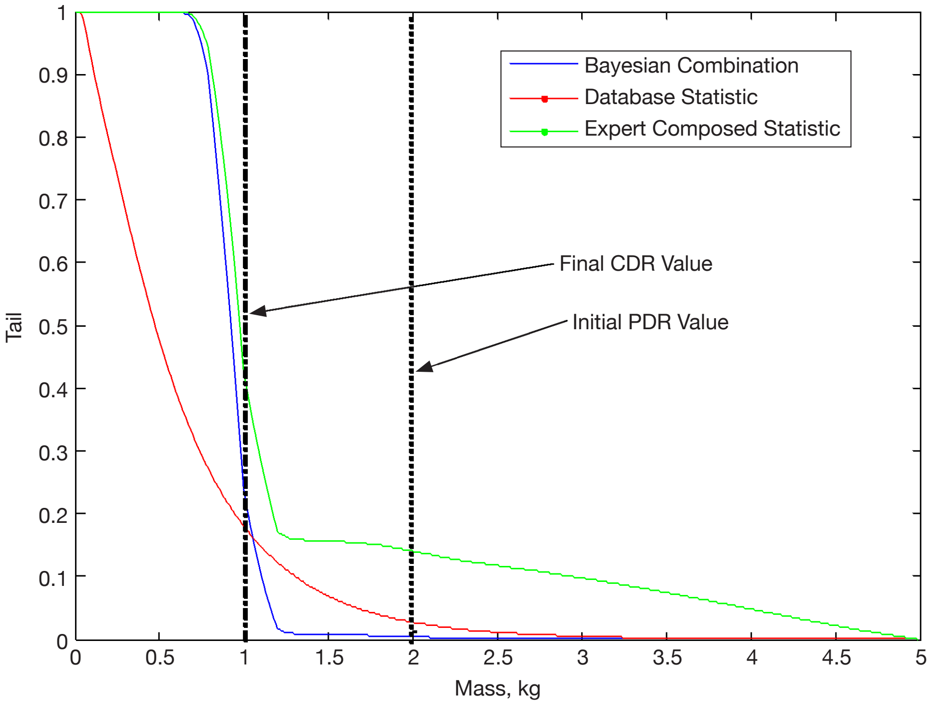

Figure 11. Tail functions for HETE-2 GPS receiver mass. The quasi-Bayesian statistic performs the best risk assessment for this case.

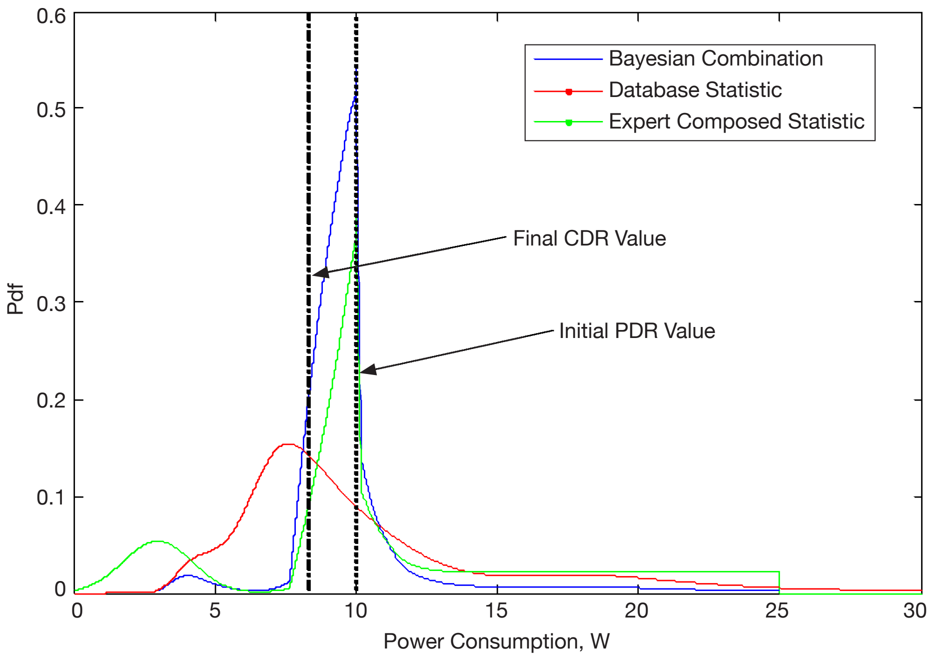

Figure 12. Probability density functions for HETE-2 GPS receiver power consumption. The data statistic identifies the final value, while the expert statistic and the quasi-Bayesian statistic are anchored on the initial (PDR) estimation.

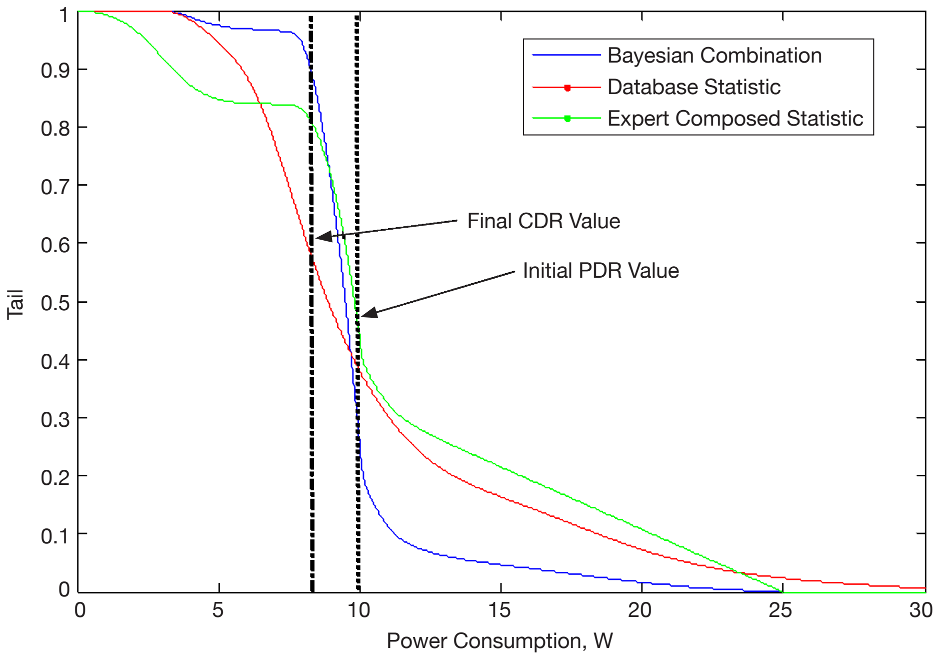

Figure 13. Tail functions for HETE-2 GPS receiver power consumption. The three statistics exhibit heavy tails. The quasi-Bayesian statistic provides the most satisfactory risk estimation.

D. Comparison with the Traditional Approach: Guidelines and Limitations

A comparison between statistical risk analysis (using quasi-Bayesian statistics) and the traditional approach is shown in Table 1. The columns of the table are:

- Name of the test case.
- CDR value (as known from technical documentation). The CDR value is the actual final mass or power value for each of the components analyzed.
- Traditional approach. This column shows the PDR value plus the contingency allocated (10 percent), together with a quantification of whether the PDR value is an over- or an underestimation with respect to the final CDR value.
- The SRE approach. This column shows the mass and power allocations with contingency sized in function of the risk: the criterion is to allow for a maximum risk of 10 percent. The result column quantifies also whether the PDR allocation determined by the model is an over- or an underestimation with respect to the final CDR value. The last column indicates whether the performance of the new method is better, the same, or worse than the traditional approach.

The test cases are also color-coded in Table 1 as follows:

- Yellow: statistical risk estimation slightly improves the risk assessment at PDR, but the sizing of the contingency is identical to the one obtained by applying contingency (no improvement).
- Green: statistical risk estimation improves risk assessment at PDR, and the contingency sized with the statistical method is closer to the final CDR value and/or allows the designer to save on mass and power allocations.

For HETE-2, six test cases were discussed: four are green and two are yellow. Statistical risk estimation improves risk assessment and the sizing of contingency in most of the cases. The guidelines inferred from comparing the test cases to the state-of-the-art approach are:

(1) The SRE technique developed performs better in most of the cases.

(2) Sizing contingency by using SRE allows savings in mass/power allocation if the initial estimate is an overestimation.

(3) Across the three statistical techniques, quasi-Bayesian composition seems to exhibit the most satisfactory performance. This is because it uses a combination of real (measured) data and of experts` opinions. Experts provide additional information thanks to their ability of interpreting data and trends in their field of expertise.

Table 1. Summary of the HETE-2 test case.

		Traditional Approach			SRE Model		
Test Case	CDR Value	PDR + Contingency	Result	Estimated Risk of Exceeding PDR (Thesis Model)	PDR with 10% Risk	Result	Comparison with Traditional Approach
HETE-2 antenna mass (S-band)	0.18 kg	0.22 kg	Over by 22%	10%	0.2 kg	Over by 11%	Better
HETE-2 transceiver mass (S-band)	1.72 kg	1.65 kg	Under by 4%	94%	1.8 kg	Over by 4%	Same
HETE-2 transceiver power consumption (S-band)	39.2 W	33 W	Under by 15%	40%	37.5 W	Under by 4%	Better
HETE-2 antenna mass (GPS)	0.33 kg	0.22 kg	Under by 33%	91%	0.33 kg	Exact value	Better
HETE-2 GPS receiver mass	1 kg	2.2 kg	Over by 120%	1%	1.2 kg	Over by 20%	Better
HETE-2 GPS receiver power consumption	8 W	11 W	Over by 37.5%	20%	11 W	Over by 37.5%	Same

IV. Conclusion

This article describes the application of the SRE methodology to the HETE-2 mission.

The analysis of the HETE-2 test case shows that in this case, data statistics were effective in identifying the final values of mass and power of a component, since the peaks of those distributions are typically close to the final CDR values. This result has been observed for the GPS antenna mass, for the S-band transceiver power consumption, and for the GPS receiver power consumption. On the other hand, expert statistics provided better assessments of the risk (as shown in tail functions), for almost all the test cases except for the GPS receiver mass. The tail functions estimated using the expert approach showed that if experts in the field have enough confidence in their estimations, the contingency allocation can be reduced compared to the contingency derived data statistics. The quasi-Bayesian approach combines the two statistics and provides a "middle-of-the-road" estimation for the design values and the contingencies: tails are very light and the peaks of the distributions generally lie between the data statistics and expert statistics for the test cases analyzed. Despite some differences, all three statistics identify problems of overestimation or underestimation in the test cases discussed.

Future work will focus on modeling interactions and dependencies between the different system metrics. So far, the two metrics of mass and power are treated as independent metrics due to statistical reasons described in [2]. Future work will focus on modeling those dependencies.

Acknowledgments

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References

[1] A. Babuscia and K.-M. Cheung, "Statistical Risk Estimation for Communication System Design — A Preliminary Look," *The Interplanetary Network Progress Report*, vol. 42-188, Jet Propulsion Laboratory, Pasadena, California, pp. 1–33, February 15, 2012. http://ipnpr.jpl.nasa.gov/progress_report/42-188/188B.pdf

[2] A. Babuscia and K.-M. Cheung, "Statistical Risk Estimation for Communication System Design," *IEEE Systems Journal*, vol. PP, no. 99, pp. 1–12, 2012.

[3] V. Cortellessa, K. Goseva-Popstojanova, K. Appulkkutty, A. R. Guedem, A. Hassan, et al., "Model-Based Performance Risk Analysis," *IEEE Transactions on Software Engineering*, vol. 31, no. 1, pp. 3–20, January 2005.

[4] L. Meshkat, "A Holistic Approach for Risk Management During Design," *IEEE*, 2006.

[5] F. Barrientos, I. Tumer, and D. Ullman, "Design Teams, Complex Systems, and Uncertainties," *IEEE*, 2005.

[6] W. L. Oberkampf, J. C. Helto, C. A. Joslyn, S. F. Wojkiewicz and S. Ferson, "Challenge Problems: Uncertainty in System Response Given Uncertain Parameters," *Reliability Engineering and System Safety*, vol. 85, nos. 1–3, pp. 11–19), July–September 2004.

[7] Y. Asnayr, V. Bryl, and P. Giorgini, "Using Risk Analysis to Evaluate Alternatives," *IEEE*, 2006.

[8] M. Fuchs and A. Neumaier, "Autonomous Robust Design Optimization with Potential Xlouds," *International Journal of Reliability and Safety*, vol. 3, nos. 1–3, 2009.

[9] M. Fuchs, A. Neumaier, and D. Girimonte, "Uncertainty Modeling in Autonomous Robust Spacecraft System Design," *Proceedings in Applied Mathematics and Mechanics*, October 15, 2007.

[10] M. Fuchs and A. Neumaier, "Potential Based Clouds in Robust Design Optimization," *Journal of Statistical Theory and Practice*, issue on Imprecision of Statistics and Applied Mathematics, vol. 3, no. 1, pp. 225–238, March 2009.

[11] A. Babuscia and K. Cheung, "An Approach to Perform Expert Elicitation for Engineering Design Risk Analysis: Methodology and Experimental Results," *Journal of the Royal Statistical Society*, vol. 177, no. 2, pp. 475–497, February 2014.

[12] A. Babuscia, K.-M. Cheung, and D. W. Miller, “Statistical Risk Estimation for Communication System Design: Development of Optimization Frameworks,” IEEE Aerospace Conference, Big Sky, Montana, 2013.

[13] A. Babuscia, “Statistical Risk Estimation for Communication System Design,” Ph.D. Thesis, Massachusetts Institute of Technology, 2012.

[14] HETE-2 Team, “HETE Ground Station Network.” http://space.mit.edu/HETE/ground_stations.html