SUBMARINE HUNTING AND OCEAN WORLDS : THE IMPORTANCE OF ASKING THE RIGHT QUESTIONS.

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Introduction: Making the most effective progress given finite resources demands dispassionate quantitative evaluation of what that progress is. Only with that definition, and an estimation of the expectation value of progress for different methodologies, can the most appropriate methodologies be selected.

As an island nation reliant on ocean-borne supplies, the United Kingdom in World War II faced a severe threat from U-boat attacks on shipping. The dismal effectiveness of countermeasures prompted the introduction of 'Operations Research' (OR, [1,2]), the evaluation and improvement of techniques, tactics and technology. Although sophisticated statistical approaches were sometimes required, often the quantitative aspects of the problem were rather simple, the challenge was to *ask the right questions*. Spectacular improvements in the effectiveness of air attacks against U-boats resulted from, for example, fuzing depth charges to shallower depths, painting the underside of aircraft white (to make them harder to spot against the sky), and reconfiguring maintenance schedules. In the latter example, defining the success metric was key : effectiveness was originally measured in the fraction of aircraft serviceable at one time (desirably ~75%) but what actually mattered was the number of missions flown. Analysis showed this could be increased even with serviceability rates as low as 50%, and rearranging (and in fact reducing) maintenance led to an improvement in combat effectiveness. It may be that analogous considerations in Ocean Worlds Exploration (OWE) lets us achieve more within a finite resource envelope.

What is Progress?: Scientifically, progress may be constituted by improved knowledge in a large number of areas. This may be difficult to quantify, although we should try. In any one domain, we might consider a single scientific question, such as the improved accuracy of determination of a single parameter, or the likelihood of a binomial (yes/no) answer to a question, e.g. 'is there life on Europa?' In the binomial case, progress can be quantified (e.g. [3]) by the incremental information value defined by the change in logarithmic odds ratio. Odds ratios have found application in clinical trials In this paradigm, the improvement in knowledge of the question 'Is there life on Mars' was advanced from an estimated 50% likelihood to 1-2% (by one investigator [4]), a knowledge gain of 17 decibans or ~6000 millibits [3]. It is important to recognize that such a Bayesian logic metric requires quantification of uncertainty prior to acquiring the measurement, as well as that afterwards. In this connection, the saga of organics discovery on Mars deserves review – the challenge has not been obtaining adequate instrumental sensitivity, but rather of refuting false positives. Thus a better strategy [5] than attempting to twice confirm a Europa Lander positive detection [6] may be to subsequently attempt to sample material unlikely to host a biosignature, and thereby eliminate the possibility of artifacts or contamination.

Expected Value: Like OR in WWII, review of performance may require us to confront uncomfortable realities in order to realize the best way forward. A review of landed in-situ missions [3] indicates that the historical probability of successful planetary landing is ~66%, and the conditional probability of successful in-situ sample acquisition and analysis is ~64%, so the combined likelihood of obtaining the desired scientific result from a single new lander might be only ~42%. Such considerations underscore the need for programmatic resilience (such as multiple landers, improved reconnaissance of landing sites, etc.) and the importance of mechanism testing and landed operations schedule margins to permit sampling re-attempts. Any estimate of expected science value of some data discussed the previous section must be conditioned by a realistic estimate of the probability of acquiring that data.

The Right Answers: An engineering design is usually aimed to be an optimum, but this obviously depends on the cost function being optimized [7]. It is not clear that the cost function in OWE has been identified. One might speculate that efforts to date have pursued a function of the form 'What is the minimum mission that has a non-zero (albeit small) probability of achieving a biosignature detection?', a criterion which if applied to fiscal investment guides the purchase of lottery tickets. A more rational function might be 'What architecture maximizes the expectation value of scientific return?' Community discussion of this question is advocated.

References: [1] Waddington, C. (1973). *OR in World War 2: Operational Research against the U-boat*. London: Elek [2] McCloskey, J. F. (1987). *Operations Research* 35(3):453-470. [3] Lorenz, R. (2019) *Adv. Space Res*. (submitted). [4] Cooper, H. S. (1980). *The search for life on Mars*. Holt, Rinehart and Winston, NY.*[5] Lorenz, R. D. (2019) Nature Astronomy (submitted) [6]* Hand, K.P. et al. (2017), *Report of the Europa Lander SDT*. NASA. [7] Lorenz, R. D. (2018) Aerospace America, June 2018, 40-43.