Evaluating Biosignatures for Life Detection

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Introduction: The goal here is to develop a conceptual framework for evaluating the ability of different biosignatures to provide evidence for the presence of life in planned missions or observational studies. The focus is on intrinsic characteristics of biosignatures in a given space environment rather than on their detection, which depends on the current state of technology. Suitable evaluation procedures are based on an extensive body of previous work on related problems in which different options are evaluated to make decisions in business, engineering, medical fields and social or political arena. In these cases, three approaches have proven to be particularly useful. Two of them, signal detection theory (SDT) and Bayesian hypothesis testing are based on probabilities. The third approach, multi-attribute utility (MAU) is based on utility theory.

Probability-based Theories: In SDT it is assumed that a signal (life) elicits response, which is the presence of a biosignature. In the absence of life there is no response. These two outcomes are called, respectively, "true positives" and "true negatives." The response to the signal, however, might be incorrect. If a biosignature is present from abiotic sources in the absence of life, the outcome is called false positive. If no biosignature is detected even though life is present, the outcome is called false negative. The goal of SDT is to estimate the probabilities of all four possible outcomes. These probabilities, however, are not independent. True positives and false negatives sum to 1, as do true negatives and false positives. Thus, two independent probabilities have to be estimated. Once this is done, each biosignatures can be assessed on the basis of an aggregate index that depends of a weighted sum of probabilities of false positives and false negatives. It reaches the maximum if both probabilities are equal to zero, i.e. the relation between life and a biosignature is unambiguous. The choice of the weight depends on whether we emphasize avoiding false positives or false negatives. In this respect, the weight can be considered a "mission objective parameter." Another measure is likelihood ratio, which is the ratio of probabilities of true positives to false positives. Since these probabilities can be interpreted, respectively, as "signal" and "noise", this is a measure of signal/noise ratio.

Another probabilistic approach is based on Bayesian hypothesis testing. Its inconvenient feature is that it depends on prior belief about the probability that life is present at the target. The assignment of this probability is subjective and might differ widely even between experts, leading to the correspondingly different evaluation biosignatures. If ample data were available, the dependence on the prior would be greatly reduced. In life detection, however, obtaining such data cannot be expected. Fortunately, it can be proven that the influence of the prior disappears when two biosignatures are compared. Then, their relative value depends only on their likelihood ratios. The same result is obtained if the likelihood ratio is used as the evaluation index in SDT.

In many instances, probabilities defined in SDT might be difficult to estimate because the ability to observe a biosignature if life is present or absent does not arise from a single process but instead is an aggregate property that depends on a series of steps. For example, a biosignature can be generated either biologically or abiotically and subsequently may survive or be degraded in the environment. Each constituent step is associated with a probability. These probabilities are more elemental than the probabilities in SDT and, therefore, are expected to be easier to estimate reliably. Once all of them are assigned, the probabilities required in SDT are evaluated with the aid of the standard probability calculus.

Utility Theory: An alternative approach to evaluating biosignatures is based on multi-attribute utility (MAU) theory. In this approach, evaluation criteria are initially identified and assigned weights that depend on their relative importance. The weights do not depend on biosignatures. Then, the utility of a biosignature is evaluated on each criterion. The overall utility of this biosignature is the weighted sum of these utilities. Compared to SDT, MAU is simpler to evaluate but the outcomes are more difficult to interpret.

Knowledge Base: Evaluation of probabilities or utilities should be entirely based on complete, currently available knowledge. This knowledge consists of information and evidence bearing on the relation between detecting biosignatures and their biological or abiotic origins. The inherently interdisciplinary, highly diverse nature of knowledge, exceeding expertise of a single scientist, necessitates creating a knowledge base (KB) that forms the common, factual basis for the evaluation process. The structure of the KB should be such that it supports evaluation. It is argued that the Hypothesis Browser for Astrobiology, a community based, curated KB for that is currently being developed, has such structure and can be readily adopted for life detection.

Elicitation and Uncertainty Quantification: To make decisions or evaluations, knowledge about a subject matter has to be translated to probabilities and/or utilities. This process is called elicitation and involves, at some stage, human judgment that is always prone to perceptual and cognitive biases. This has to be acknowledged and reduced through, for example, proper choice of measurement scales. This will be discussed in a general context of uncertainty quantification, an essential step for determining the reliability of evaluations, especially when knowledge is incomplete and/or uncertain.