



Technosignatures: Frameworks for Their Assessment

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Abstract

In view of the promising advancements in technosignature science, the question of what constitutes a robust technosignature is rendered crucial. In this paper, we first delineate a Bayesian framework for ascertaining the reliability of potential technosignatures by availing ourselves of recent cognate research in biosignatures. We demonstrate that ideal technosignatures must not only have low risk of stemming from false positives but also evince sufficiently high prior probability of existence. Given the inherent difficulties with estimating the latter, we highlight a few alternative metrics drawn from diagnostic testing such as the Youden index that bypass the requirement of explicitly calculating the prior. We apply the models (Bayesian or otherwise) to a select few technosignature candidates and show that artificial electromagnetic signals, chlorofluorocarbons, and artifacts perform well on this front. While these results may be along expected lines, we suggest that identifying and developing suitable approaches to further evaluate technosignature candidates is of considerable importance.

Unified Astronomy Thesaurus concepts: [Astrobiology \(74\)](#); [Search for extraterrestrial intelligence \(2127\)](#); [Technosignatures \(2128\)](#); [Bayesian statistics \(1900\)](#); [Bayes' Theorem \(1924\)](#)

1. Introduction

The notion of searching for signatures of extraterrestrial technology is more than a century old insofar as the scientific literature is concerned (Dick 1993), with the early paper by Barnes (1931) on artificial electromagnetic signals representing a notable example. The modern era of this field can be argued to have originated in the 1950s and 1960s owing to a spate of well-known publications (Coconi & Morrison 1959; Purcell 1960; Bracewell 1960; Dyson 1960; Drake 1961; Schwartz & Townes 1961; von Hoerner 1961; Sagan 1963; Drake 1965; Shklovskii & Sagan 1966), many (albeit not all) of which advocated searching for electromagnetic signals.

Ever since that time period, the realm of technosignatures—an apposite term coined by Tarter (2007)—has broadened to encompass multiple search strategies and novel signatures of extraterrestrial technology. State-of-the-art reviews of this subject are furnished in Tarter (2001), Bradbury et al. (2011), Cabrol (2016), Lingam & Loeb (2019), Lingam & Loeb (2021), Wright (2021), and Haqq-Misra et al. (2022c), among other sources. The search for technosignatures is embedded within the larger domain of astrobiology (Tarter 2004; Wright 2018).

However, in light of the limited information available hitherto in astrobiology and technosignatures in particular, as well as the myriad unknowns, it becomes necessary to quantify these uncertainties and address the objectives of these subjects through a probabilistic lens. In other words, how can we judge the “quality” of a reported technosignature candidate detection? One of the most common avenues for achieving this broad goal

is to rely on the tried-and-tested paradigm of Bayesian inference (Berger 1985; Jaynes 2003; Howson & Urbach 2006; von Toussaint 2011; Lindley 2013). It is hardly surprising, therefore, that Bayesian methods now comprise an integral component of the sciences.

In astrobiology, Bayesian techniques are being increasingly employed in a diverse array of settings ranging from Earth to exoplanets (e.g., Waltham 2011; Spiegel & Turner 2012; Walker 2017; Chen & Kipping 2018; Balbi & Grimaldi 2020; Kipping 2020; Truitt et al. 2020). For instance, they have been advocated and/or used to gauge the viability of potential biosignatures (Lorenz 2019a, 2019b; Pohorille & Sokolowska 2020; Affholder et al. 2021), to wit, markers of extraterrestrial biology. In this context, the significance of Bayesian frameworks for assessing the plausibility of in situ and exoplanet biosignatures was underscored in impactful and wide-ranging explorations of the subject by Catling et al. (2018), Walker et al. (2018), and Meadows et al. (2022).

In the area of studying technosignatures, Bayesian approaches to the famous Drake equation (Drake 1965; Shklovskii & Sagan 1966; Vakoch et al. 2015), the Fermi paradox (Brin 1983; Cirkovic 2018b; Forgan 2019), and related topics have been propounded (see Wilson 1984; Glade et al. 2012; Haqq-Misra & Kopparapu 2012; Lacki 2016; Verendel & Häggström 2017; Grimaldi & Marcy 2018; Sandberg et al. 2018; Bloetscher 2019; Whitmire 2019; Snyder-Beattie et al. 2021). However, applications of this methodology to infer the soundness of technosignature candidates themselves are lacking. This lacuna is somewhat unexpected at first glimpse because technosignatures are arguably the true focus of “technological” life in the universe. It is natural, therefore, to contend that assessments of technosignature candidates warrant the utilization of Bayesian techniques (Haqq-Misra et al. 2019;



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Lingam & Loeb 2021; Balbi & Grimaldi 2022), much like biosignatures, which are basically their nontechnological analogs.

As noted above, to the best of our knowledge, no systematic Bayesian analysis of what are the attendant unknowns and issues when dealing with putative technosignatures has ever been instantiated. In this paper, we explore this topic by explicitly paralleling the formalism elucidated in Catling et al. (2018, their Section 2). We wish to highlight that some of the ensuing results are already recognized in technosignature research but often at an informal level and/or in the gray literature. The situation with respect to biosignatures is different because formal analyses of this kind have emerged recently (e.g., Catling et al. 2018; Pohorille & Sokolowska 2020; Foote et al. 2022).

The outline of the paper exhibits the following structure. We explicate the Bayesian framework in Section 2 and delve into its general and specific ramifications in Section 3. However, as we shall demonstrate, the Bayesian approach is confronted with the fundamental issue of oft-indeterminate priors. Hence, we sketch some alternative diagnostics of potential technosignatures in Section 4 and summarize our findings in Section 5.

2. The Bayesian Framework

As stated in Section 1, our mathematical approach is essentially equivalent to that of Catling et al. (2018, their Section 2). However, to make our exposition self-contained, we will delineate the salient steps of the Bayesian framework presented in Catling et al. (2018). Our emphasis is on simplicity, owing to which some of the model details can be generalized. For instance, instead of binary variables (i.e., only two outcomes are feasible) and probabilities, one could introduce continuous variables and probability distribution functions.

We commence with a description of our core notation and definitions that will be used hereafter:

1. The data or signal detected, which is suggestive of a technosignature candidate, is denoted by “ D .”
2. The hypothesis that recognizable extraterrestrial technology generates D is denoted by “ T .”⁸ We emphasize the word “technology” in lieu of extraterrestrial technological intelligence (ETI) since technology may go on functioning and producing technosignatures long after its source ETI has vanished (Holmes 1991; Ćirković et al. 2019). In fact, even derelict technology can engender technosignatures on long timescales (Wright 2021).
3. We employ the notation “ $\bar{T}$ ” for the exact opposite of T , namely, that no such recognizable extraterrestrial technology (in some fashion) produces D (which thus stems from nontechnological activity); to put it differently, extraterrestrial technology responsible for a specific technosignature candidate is effectively treated as a binary hypothesis.
4. Under the broad umbrella of “ C ,” we include all contextual information that is *not* encompassed by D . For instance, data on habitability or putative biosignatures of the world

(from which D is derived) would provide valuable context. This category would contain any other information gained from a theoretical perspective that furnishes context for interpreting and comprehending D . Lastly, C also incorporates contextual information pertaining to the detecting instrument; this kind of information may not have a direct bearing on regulating the magnitude of $P(T|C)$ introduced later.

The primary objective is to determine $P(T|D, C)$, which encapsulates the *posterior* probability of the hypothesis T being correct given the signal D and contextual information C . To calculate $P(T|D, C)$, we invoke Bayes’s theorem that is expressible as

$$P(H|D) = \frac{P(D|H)P(H)}{P(D|H)P(H) + P(D|\bar{H})P(\bar{H})}, \quad (1)$$

where “ H ” is the hypothesis in question and “ D ” is the associated data/signal. In the above formula, $P(H|D)$ is the posterior probability, and $P(H)$ is the prior probability representing the probability of H being true; $P(D|H)$ and $P(D|\bar{H})$ are the probabilities of the data D arising when the hypothesis is true and false, respectively. The implicit assumption in Equation (1) is that H is a binary hypothesis, which mirrors our earlier stipulation. We remark that the sum of $P(D|H)$ and $P(D|\bar{H})$ is not necessarily equal to unity; a related scenario is clarified in Haqq-Misra & Kopparapu (2012, Section 3).

On applying Bayes’s theorem, Equation (1), to compute the posterior $P(T|D, C)$, we end up with

$$P(T|D, C) = \frac{P(D, C|T)P(T)}{P(D, C|T)P(T) + P(D, C|\bar{T})P(\bar{T})}. \quad (2)$$

Next, we employ Bayes’s theorem twice to determine $P(D, C|T)$ and $P(C|T)$, along with their counterparts for $\bar{T}$; the intermediate steps are elucidated in Catling et al. (2018, their Equation (7)) and Lingam & Loeb (2021, Section 6.8). It is found that Equation (2) is transformed into

$$P(T|D, C) = \frac{P(D|C, T)P(T|C)}{P(D|C, T)P(T|C) + P(D|C, \bar{T})P(\bar{T}|C)}. \quad (3)$$

It is worth unraveling what the various terms in this equation imply. For a given context (C), $P(D|C, T)$ is the likelihood of the data D arising through the action(s) of extraterrestrial technology. In contrast, $P(D|C, \bar{T})$ embodies the likelihood of D being generated in the *absence* of extraterrestrial technology.

It is important to recognize that the same signal D may manifest due to a combination of extraterrestrial technology and nontechnological avenues. If the signal is generated predominantly or exclusively by extraterrestrial technology, then we would anticipate the ratio $P(D|C, T)/P(D|C, \bar{T})$ can become orders of magnitude larger than unity (and formally approach infinity). On the other hand, if D is readily generated by nontechnological sources of extraterrestrial origin, then this ratio may become small (i.e., orders of magnitude lower than unity in limiting cases). Lastly, if both extraterrestrial technology and nontechnological pathways have a similar likelihood of producing the signal, it is reasonable to presume that $P(D|C, T)/P(D|C, \bar{T})$ is of order unity or thereabouts. We revisit this ratio in Equation (5) and the accompanying discussion thereafter.

⁸ We do not deal with the case where extraterrestrial technology is functional but not responsible for D . The reason for this exclusion is that we focus on some particular signal (e.g., atmospheric pollution), and the thrust is toward determining the sources (technological or otherwise) that engender this signal; in other words, T is “selected” for a specific D .

$P(T|C)$ and $P(\bar{T}|C)$ represent the probabilities for the existence and absence, respectively, of recognizable extraterrestrial technology (linked to D) after taking C into consideration. These two quantities loosely resemble the priors $P(T)$ and $P(\bar{T})$ but are *not* identical to them because of the added context C . Moreover, T refers to a specific type of recognizable extraterrestrial technology that has the capacity to generate the D in question. Hence, it is necessary to avoid conflating $P(T|C)$ with generic (prior) probabilities for the existence of ETIs or extraterrestrial technology.

At this juncture, a brief digression concerning $P(T|C)$ is warranted. Note that $P(T)$ basically corresponds to the prior probability of the existence of recognizable extraterrestrial technology of a particular kind that produces D . It shares a close connection with the composite factor $f_{ti} \equiv f_i \cdot f_c$ in the Drake equation (Drake 1965), which quantifies the likelihood of the emergence of communicative ETIs,⁹ refer to the discussion in Glade et al. (2012, their Section 2.1). If we turn our attention to $P(T|C)$, it is clearly distinct from f_{ti} because the latter is interpreted as the mean estimate for the galaxy, whereas the former must be strictly evaluated on a case-by-case basis by incorporating C for a particular form of extraterrestrial technology associated with D .

As indicated by its definition, the magnitude of $P(T|C)$ changes depending on the available context, as illustrated by the following thought experiment. If we detect some signal from empty space, we have (virtually) no contextual information. On the other hand, if the same signal is traceable to a planet, different levels of C are conceivable. Knowing that the planet is (a) terrestrial, (b) in the habitable zone, (c) endowed with an atmosphere and liquid water bodies, and (d) producing biosignatures, can successively raise the value of $P(T|C)$ in turn when each layer of knowledge is added.

In the most extreme optimistic scenario, wherein “constellations” of technosignatures exist on the same world (one such hypothetical outcome with respect to energy harvesting is delineated in Lingam & Loeb, 2017), $P(T|C)$ might approach unity thanks to the wealth of contextual information. For example, if narrowband electromagnetic signals (C in this instance) emblematic of ETI are detected, it is plausible that $P(T|C) \sim 1$ when we encounter, say, atmospheric spectral signatures characteristic of chlorofluorocarbons (CFCs; the data D in this case). In qualitative terms, the fact that we have encountered a technosignature of one kind (viz., the context) makes it much more likely that another technosignature candidate (i.e., the data) from the same provenance would arise from extraterrestrial technology.

Circling back to Equation (3), it is possible to recast the expression and simplify it. We invoke the previous assumption about $\bar{T}$ and T serving as diametrical opposites, which enables us to utilize the relation

$$P(\bar{T}|C) = 1 - P(T|C). \quad (4)$$

Next, we introduce the parameter ξ defined as follows:

$$\xi = \frac{P(D|C, T)}{P(D|C, \bar{T})}. \quad (5)$$

⁹ Note that f_i is the fraction of habitable worlds that support life, f_c is the fraction of life-bearing worlds that develop intelligence, and f_e is the fraction of worlds with intelligent entities that develop (communicative) technology (Drake 1965).

This ratio is inherently linked with quantifying the impact of false positives. The reason stems from the definitions of $P(D|C, T)$ and $P(D|C, \bar{T})$ in the paragraph below Equation (3). For a particular context (C), ξ embodies the ratio of the probability of the data ensuing from extraterrestrial technology and the probability of the same data originating from extraterrestrial nontechnological sources. In other words, a high value of $\xi \gg 1$ indicates that false positives are rendered relatively unimportant, which is advantageous as delineated hereafter. When the converse is true (viz., false positives are predominant), it would translate to low values of $\xi \ll 1$. Before moving on, we point out that ξ directly ties in with the “ambiguity” axis of the technosignature rubric expounded by Sheikh (2020). More precisely, $\xi \gg 1$ is tantamount to low ambiguity and vice versa.

On invoking the definition of Equation (5) and substituting Equation (4) into Equation (3), we finally end up with

$$P(T|D, C) = \frac{P(T|C)\xi}{1 + P(T|C)(\xi - 1)}, \quad (6)$$

thereby implying that $P(T|D, C)$ is sensitive to only two parameters, to wit, $P(T|C)$ and ξ . This expression matches Catling et al. (2018), Lingam & Loeb (2021, Equation (6.74)), and Foote et al. (2022, their Figure 2) after implementing a suitable change of variables, which is completely along expected lines.

In closing, we remark on the practical significance of $P(T|C)$ and ξ for technosignature surveys. The former, $P(T|C)$, guides target selection, namely, searches aimed to maximize this quantity because it embodies the likelihood of the presence of a *specific* technosignature when searching a *specific* target. The latter, ξ , maps to the odds of false positives, essentially a measure of the ambiguity, for given signal D in a given context C ; therefore, as stated earlier, $\xi \gg 1$ would be desirable for genuine technosignature signals.

3. Implications of the Bayesian Framework

We will analyze some generic consequences emerging from Equation (6) and follow this up by examining a select few technosignature candidates with this framework.

3.1. General Ramifications

It is worth considering certain limits of Equation (6) to gauge its behavior. In the formal limit where $\xi \rightarrow \infty$ and $P(T|C)$ is not infinitesimally small, it can be shown that $P(T|D, C) \rightarrow 1$. In qualitative terms, if the risk of false positives is negligible, the probability that the data is produced by extraterrestrial technology (and not other processes) should be relatively high. In contrast, if $\xi \rightarrow 0$, the opposite trend is manifested with $P(T|D, C) \rightarrow 0$.

Next, let us tackle the scenario wherein $P(T|C) \rightarrow 1$. In this limit, we find that Equation (6) reduces to $P(T|D, C) \rightarrow 1$. This result is also readily explainable. If we have high confidence, for a specified context, that extraterrestrial technology would exist, it is reasonable to anticipate that $P(T|D, C)$ would be commensurately high. If we take the opposite limit of $P(T|C) \rightarrow 0$, we obtain $P(T|D, C) \rightarrow 0$ from Equation (6). Put simply, selecting an extremely low prior probability in a given context naturally engenders an extremely low likelihood of the data being an outcome of extraterrestrial

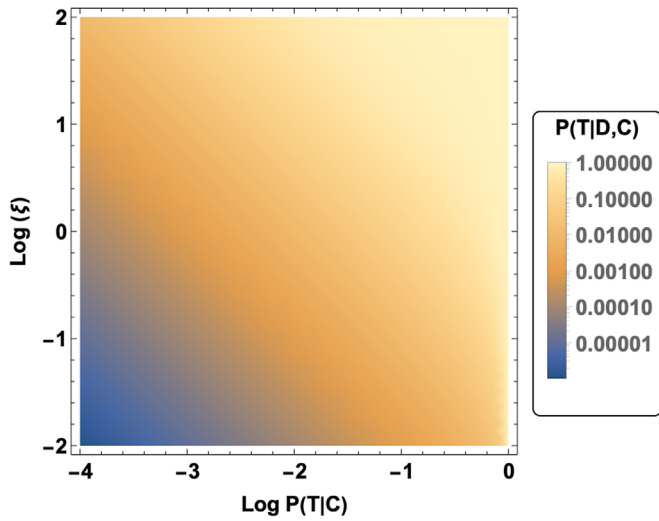


Figure 1. The posterior probability $P(T|D, C)$ that the data D is derived from extraterrestrial technology (in a particular context C) as a function of the prior probability $P(T|C)$ for the existence of recognizable extraterrestrial technology for specific C and the dimensionless ratio ξ that roughly quantifies the odds that D is due to extraterrestrial technology and not false positives (for given C).

technology. We wish to highlight that low values of the posterior are not necessarily a problem since there may exist certain signals for which one would expect to naturally achieve such values. To put it another way, we would ideally want the posterior to be low when the signal is not of ETI provenance. This aspect should be borne in mind with respect to the rest of the paper.

Moving on from analytically computing the limiting cases, we have plotted $P(T|D, C)$ as a function of ξ and $P(T|C)$ in Figure 1. It is apparent from inspecting the figure that $P(T|D, C)$ approaches unity when the product $\Gamma \equiv P(T|C)\xi$ is a few orders of magnitude higher than unity at the minimum. This result is consistent with the prior paragraphs, which demonstrated that the formal limits $\xi \rightarrow \infty$ and $P(T|C) \rightarrow 1$ permit $P(T|D, C) \rightarrow 1$ to be actualized. However, this criterion can be further refined and quantified—in the event that $\Gamma \gtrsim 1$ is valid, we notice that moderate values of $P(T|D, C)$ on the order of 0.1 may be attained.

It is possible to quantify these general observations as follows. If we were to obtain $P(T|D, C) > 0.5$, this range would represent better than even odds of T being true for given data and context. On substituting this inequality into Equation (6), we arrive at

$$P(T|C) > \frac{1}{\xi + 1}. \quad (7)$$

Note that, for $\xi \gtrsim 1$, Equation (7) can be approximated as $P(T|C) \gtrsim 1/\xi$. Therefore, as long as $\Gamma \gtrsim 1$ holds true alongside the condition $\xi \gtrsim 1$, the posterior probability $P(T|D, C)$ becomes significant. We have plotted Equation (7) in Figure 2, which illustrates most of these key points.

On the basis of our analysis so far, there are several broad conclusions that can be drawn.

1. It is evident from Figure 1 that a “substantial” region of the parameter space is characterized by $P(T|D, C) \ll 1$. Generally speaking, when $\xi \ll 1$ and/or $P(T|C) \ll 1$, the

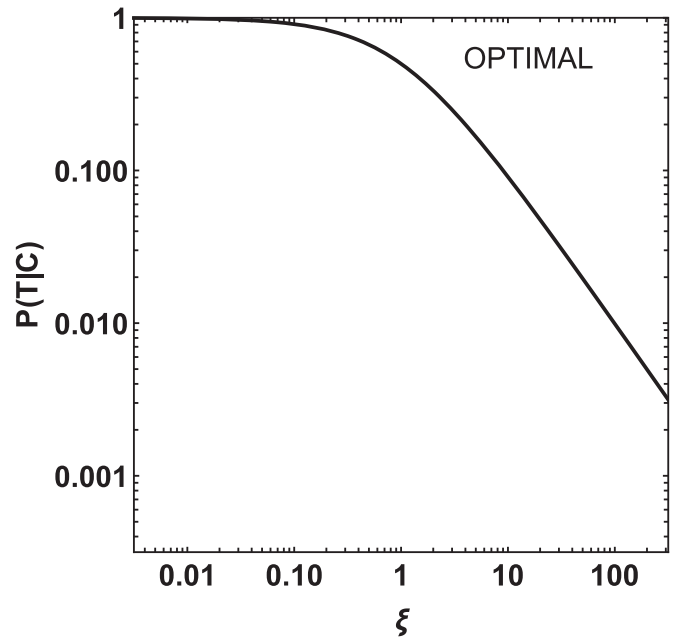


Figure 2. The prior probability $P(T|C)$ as a function of the dimensionless ratio ξ required to achieve better than even odds that the data/signal D originates from extraterrestrial technology given contextual information C ; the region above the curve labeled “optimal” meets the desired criterion. Note that $P(T|C)$ is the probability of the existence of specific recognizable extraterrestrial technology in light of C , and ξ roughly quantifies the odds that D is due to extraterrestrial technology and not false positives (for specific C).

“undesirable” outcome of $P(T|D, C) \ll 1$ could consequently arise.

2. In order for the posterior probability $P(T|D, C)$ to be significant, one might naively suppose that minimal odds of false positives (equivalent to $\xi \gg 1$) are sufficient. As a matter of fact, several classic technosignatures are associated with inherently low ambiguity, which constitutes one of their chief advantages (Shklovskii & Sagan 1966; Tarter 2001; Margot et al. 2019; Wright et al. 2022). However, it is more accurate to state that $P(T|D, C)$ is rendered significant when Equation (7), or the loosely equivalent $\Gamma \gtrsim 1$, holds true. To put it differently, except when ξ exceeds unity by many orders of magnitude, the prior $P(T|C)$ plays a vital role in determining $P(T|D, C)$. This result is not surprising, given that several publications in astrobiology have emphasized the centrality of the prior (e.g., Spiegel & Turner 2012; Verendel & Häggström 2017; Chen & Kipping 2018; Balbi & Grimaldi 2020; Affholder et al. 2021; Lineweaver 2022).
3. In view of the importance of $P(T|C)$, we are faced with a crucial issue. Given that it quantifies the probability of the existence of specific recognizable extraterrestrial technology producing D for a particular context C , this technology must be constructed by an ETI in the first place. Thus, in dealing with $P(T|C)$, we encounter a pivotal (but *not* synonymous) unknown: the probability of the existence of ETIs. This issue has attracted intense debate since at least the mid-twentieth century, with numerous scientists contending that this probability is extremely low (e.g., Simpson 1964; Tipler 1980; Mayr 1985; Diamond 1990; Ward & Brownlee 2000; Mayr 2004; Lane 2012; Snyder-Beattie et al. 2021;

Lineweaver 2022), while others have cautioned against adopting this stance universally and/or have posited a comparatively optimistic or agnostic standpoint (e.g., Sagan 1963; Bracewell 1976; Schwartzman & Rickard 1988; De Duve 1995; Sagan 1995; Ćirković 2018a; Wright et al. 2022).

Before proceeding onward to tackle select technosignature candidates, we reiterate that many of these basic points are well understood in the domain of astrobiology; the recent treatises by Foote et al. (2022) and Meadows et al. (2022) constitute two such examples. However, this formalism and its ramifications remain unexplored in the context of technosignatures.

3.2. Electromagnetic Technosignatures

Radio and optical signals from ETIs rank among the first technosignatures proposed, which occurred in the mid-twentieth century (Barnes 1931; Cocconi & Morrison 1959; Schwartz & Townes 1961). It is widely held that Cocconi & Morrison (1959) motivated the modern search for technosignatures, which is now over six decades old because it commenced in 1960 (Drake 1961).

There are manifold advantages conventionally linked with electromagnetic signals deliberately transmitted by ETIs (labeled as “electromagnetic technosignatures” for the sake of brevity), of which one is their fundamentally low ambiguity (Shklovskii & Sagan 1966; Margot et al. 2019; Sheikh 2020). The underlying reasons are succinctly described in Shklovskii & Sagan (1966) and Tarter (2001). For instance, the fractional bandwidth of astrophysical masers is typically $\sim 10^{-4}$, whereas human technology is already capable of producing electromagnetic signals with fractional bandwidths of $\lesssim 10^{-12}$ (Tarter 2001). Another conspicuous method of telling apart artificial signals is when they obey the relation $B\tau \sim 1$, where B is the channel width and τ is the signal duration (Tarter 2001), as mentioned by Drake (1965).¹⁰ The content(s) of some signals (e.g., prime number sequences) can also unequivocally highlight their technological origin.

However, a potential objection could be raised here vis-à-vis false positives. While artificial electromagnetic signals ostensibly possess exceptionally low ambiguity (in the sense of definitively stemming from technology), they may originate on/near Earth due to anthropogenic activities, thereby running the risk of being interpreted as arising from extraterrestrial technology. At this stage, the relevance of the contextual information C in Equation (5), which encapsulates the false positive odds, is apparent. With the appropriate C , one can potentially discern whether the data D is actually anthropogenic in origin.

A quintessential example of this procedure in action is Breakthrough Listen Candidate 1 (BLC-1), namely, a radio signal detected in the general direction of Proxima b and reported in 2021 by the Breakthrough Listen initiative (Smith et al. 2021). This narrowband signal at ~ 982 MHz exhibited a number of key characteristics attributed to putative electromagnetic technosignatures. However, a meticulous and rigorous analysis of the data that accounted for complex intermodulation caused by anthropogenic radio signals (viz.,

employing contextual information C) concluded that BLC-1 was of anthropogenic origin (Sheikh et al. 2021).

Therefore, if sufficient contextual information is available, the impediments posed by false positives are likely to be minimal for electromagnetic technosignatures of this kind. If we choose, say, $\xi \sim 10^4$ —because this value is indicative of very high confidence concerning the absence of false positives—we see from Equation (7) that $P(T|C) \gtrsim 10^{-4}$ is necessary to achieve the desired criterion of $P(T|D, C) > 0.5$. Although this magnitude is perceived to be conventionally “small,” we caution that some priors in the literature for the existence of ETIs generating certain types of technosignatures are far smaller, as reviewed in Lacki (2016) and Sandberg et al. (2018). Hence, as stated previously, the posterior is inherently sensitive to the specified prior.

The above exposition has implicitly emphasized radio signals, partly on account of the substantial corpus of observations accumulated since the 1960s. However, optical signals analogous to those emitted by continuous-wave or pulse lasers might be even more promising in the sense of having incredibly low odds of false positives (to wit, endowed with $\xi \rightarrow \infty$), in which case the issues posed by $P(T|D, C)$ are minimized or eliminated. After the foundational work by Schwartz & Townes (1961), several searches have been conducted or are ongoing at optical wavelengths (e.g., Howard et al. 2004; Stone et al. 2005; Schuetz et al. 2016; Tellis & Marcy 2017; Wright et al. 2018), albeit not as extensively as radio surveys.

3.3. Atmospheric Technosignatures

For many decades, the search for technosignatures was virtually synonymous with seeking out electromagnetic technosignatures. However, in the past decade, the complementary notion of searching for nonelectromagnetic technosignatures has firmly taken root (Bradbury et al. 2011; Wright et al. 2014; Lingam & Loeb 2019) although its antecedents date back to the 1960s at the minimum (e.g., Bracewell 1960; Dyson 1960).

As a consequence of the tremendous advances in exoplanetary science, searching for atmospheric biosignatures via current and next-generation telescopes is feasible (Fujii et al. 2018), using methods such as transmission spectroscopy. It is natural to conceive of atmospheric components (e.g., gases) that are manufactured by means of extraterrestrial technology instead of biology. A few candidates have been proposed in this domain, which are reviewed in Lingam & Loeb (2021, Section 9.5) and Haqq-Misra et al. (2022c).

As intimated earlier toward the end of Section 3.1, the determination of $P(T|C)$ is rife with uncertainty. Hence, we will focus primarily on ξ when evaluating the merit(s) of atmospheric technosignature candidates. In order to compute ξ , we do not need to know $P(D|C, T)$ and $P(D|C, \bar{T})$ separately but only the ratio of these two quantities. If an atmospheric component is produced at the flux Φ_T by extraterrestrial technology and with flux Φ_N by nontechnological sources, it seems reasonable to assume that $P(D|C, T) \sim C\Phi_T$ and $P(D|C, \bar{T}) \sim C\Phi_N$, where C is constant. In other words, *ceteris paribus*, we model the probabilities as being proportional to the magnitude of the associated sources on a specific world.

The above ansatz presupposes that the atmospheric abundance is proportional to the flux and that the atmospheric lifetimes of the same component generated via various

¹⁰ Signals with small values of τ (i.e., pulses) suffer significant dispersion at radio wavelengths and therefore do not arrive as pulses (Cordes & Lazio 1991). In contrast, the trade-off is not necessary in the optical: one can achieve unusually small B and τ simultaneously without the downside of dispersion.

pathways are similar to one another. This simplification has been employed in prior technosignature studies (e.g., Haqq-Misra et al. 2022a, their Section 3), *faute de mieux*, and arguably constitutes an adequate (and justifiable) starting point.¹¹ By working with this particular setup, we find that Equation (5) is reducible to

$$\xi \sim \frac{\Phi_T}{\Phi_N}. \quad (8)$$

Hence, as long as $\Phi_T \gg \Phi_N$, the technosignature candidate can be said to have low risk of false positives. We will now utilize this metric to assess two different atmospheric technosignatures by envisaging “Earth as an exoplanet” (e.g., Robinson & Reinhard 2020; Mayorga et al. 2021). We single out Earth because in-depth atmospheric data for temperate rocky exoplanets as well as the accompanying theoretical modeling to gauge the sources of atmospheric components are currently unavailable, and the Earth functions as a well-calibrated yardstick against which other worlds may be compared.

The first atmospheric technosignatures that we shall evaluate are nitrogen oxides (NO_x), especially nitrogen dioxide (NO_2), which was extensively investigated by Koppalapudi et al. (2021); this gas was also mentioned in Stevens et al. (2016). On Earth, biogenic and abiotic production of NO_x is ~ 10.6 Tg of nitrogen per year (Tg(N) yr^{-1}), whereas anthropogenic sources supply ~ 32 Tg(N) yr^{-1} of NO_x chiefly on account of combustion (Holmes et al. 2013). On invoking Equation (8) and substituting these fluxes, we obtain $\xi \sim 3$. It is evident that this value of ξ is not particularly high. In order for the posterior to attain sufficiently high values, we draw on Equation (7) to solve for the desired prior $P(T|C)$; on doing so, we estimate that $P(T|C) \gtrsim 0.25$ should hold true.

The above value of the prior is high and calls for substantial optimism with regards to the probability of the existence of specific recognizable extraterrestrial technology on the planet under investigation. When weighed against the publications cited in point #4 of Section 3.1, we note that several of them contend that the probability of ETIs are many orders of magnitude lower than our estimate. A potential avenue for $P(T|C)$ to attain high values is when the contextual information C boosts the prospects for extraterrestrial technology; for example, this outcome might transpire if biological signatures of life—especially complex life (refer to Schulze-Makuch & Bains 2018)—were to be detected on the same world. To put it another way, the presence of (nontechnological) life could provide important contextual information that would increase the possibility that the data implicated the presence of extraterrestrial technology.

In conclusion, unless the existence of extraterrestrial technology is distinctly favored because of the context C and/or future *a priori* grounds, it is plausible that NO_x would not be a strong technosignature candidate owing to the relatively modest magnitude of ξ . However, a crucial caveat is worth highlighting. The anthropogenic production of NO_2 has declined by a factor of ~ 4 in the last four decades,¹² implying that $\xi \sim 12$ in the past. Even higher values of $\xi \gg 1$

are conceivable on worlds that possess large-scale technospheres and minimal biospheres; these worlds were briefly described in Wright et al. (2022) and christened “service worlds”.

The next atmospheric technosignatures we consider are CFCs. These compounds have been utilized in various industrial applications, most notably (and notoriously) as refrigerants but also in the manufacture of aerosol sprays and packing materials. In addition, CFCs are potent greenhouse gases and could be used, at least in principle, to raise the surface temperature of certain worlds (Marinova et al. 2005). The notion that CFCs comprise a viable technosignature candidate has an unexpectedly long history (Owen 1980; Campbell 2006; Schneider et al. 2010), but the first quantitative assessment of their detectability was performed for exoplanets orbiting white dwarfs by Lin et al. (2014). The paper by Haqq-Misra et al. (2022b) explored the detectability of CFCs on M-dwarf exoplanets (including the well-known TRAP-PIST-1e).

We are now in a position to repeat the analysis for CFCs previously undertaken for NO_x . We select trichlorofluoromethane (CFC-11) and dichlorodifluoromethane (CFC-12) because these molecules were thoroughly investigated by Haqq-Misra et al. (2022b). Due to our emphasis on ξ , it is necessary to quantify Φ_T and Φ_N . However, we are confronted with an interesting situation when attempting to do so. For the preceding molecules, there are no documented nonanthropogenic sources (Seinfeld & Pandis 2016); some other short-lived halocarbons (not CFCs) in the atmosphere are intriguingly synthesized by phytoplankton (Lim et al. 2017).

Thus, it is safe to aver that $\Phi_T \gg \Phi_N$ for CFC-11 and CFC-12 on Earth. Quantifying the ratio of these two fluxes is challenging because of the lack of constraints on Φ_N to the best of our knowledge. However, for the sake of illustration, we select $\xi \sim 10^4$ in the same vein as Section 3.2. After substituting this value into Equation (7), we find that $P(T|C) \gtrsim 10^{-4}$ is desirable to obtain a high value of the posterior probability for the existence of recognizable extraterrestrial technology.

On the basis of our discussion, it is tempting to conclude that CFCs are trustworthy technosignature candidates by virtue of $\xi \gg 1$. However, even setting aside the major unknown—namely, the prior $P(T|C)$ —there are attendant subtleties. On worlds other than Earth, nontechnological pathways might exist for the synthesis of CFCs,¹³ in which case Φ_N would be nonnegligible and ξ could diminish in turn. On the other hand, on service worlds or heavily industrialized planets, Φ_T can be orders of magnitude higher than Earth, which may boost ξ commensurately if Φ_N is relatively unaffected.

3.4. Artifact Technosignatures

The categories investigated hitherto (electromagnetic and atmospheric technosignatures) are restricted to remote detection using space- and ground-based telescopes where the contextual information C might be limited; on the other hand, C might become high in certain scenarios delineated in Section 2. With access to limited C in general, it is plausible that $P(T|C)$

¹¹ A full-fledged treatment of $P(D|C, T)$ and $P(D|C, \bar{T})$ is rendered profoundly difficult because we would require comprehensive understanding of the geological, physical, chemical, biological, and technological processes permissible on this world.

¹² <https://www.epa.gov/air-trends/nitrogen-dioxide-trends>

¹³ This issue is effectively the same as the problem of “unconceived alternatives” encountered in the philosophy of science (Stanford 2006; see also Mill 1846, p. 296). This aspect, along with the aforementioned hurdle of determining priors, was articulated vis-à-vis ETIs by Vickers (2020) and Cowie (2021, 2023).

may be lower for some technosignatures, which runs counter to the goal of maximizing this quantity to the extent feasible insofar as genuine technosignatures, and not spurious signals masquerading in this fashion, are concerned.

However, another example of technosignatures merits consideration, to wit, the possibility of discovering physical artifacts of extraterrestrial technology within the solar system (Freitas 1983; Bradbury et al. 2011; Haqq-Misra & Kopparapu 2012; Lacki 2019; Shostak 2020). This notion was broached by Bracewell (1960) in a well-known publication, after which a handful of searches for artifacts have been conducted in geosynchronous Earth orbits (Villarroel et al. 2022a, 2022b), at the Earth–Moon Lagrange points (Freitas & Valdes 1980; Valdes & Freitas 1983; Freitas & Valdes 1985), and on the lunar surface (Arhipov 1995; Lesnikowski et al. 2020). Artifact searches could potentially be initiated for objects in proximity to Earth (Steel 1995; Arhipov 1996; Benford 2021; Loeb & Laukien 2022); co-orbital objects (Benford 2019); or objects located on the surfaces of planets and moons (Carlotto & Stein 1990; Arhipov et al. 1996; Davies & Wagner 2013). This endeavor can be pursued either passively through remote sensing characterization or actively by conducting in situ spacecraft measurements.

As with electromagnetic technosignatures in Section 3.2, the hypothetical detection of an artifact candidate within the solar system would first raise the immediately obvious possibility that this technology actually originates from Earth. Resolving this matter will necessitate sufficiently in-depth acquisition and analysis of the contextual information C in order to discern whether or not the obtained data D is terrestrial (i.e., human) in origin. For instance, a slow-moving object endowed with a highly variable light curve was detected in 2013 and theorized to represent either a tumbling near-Earth asteroid or an uncatalogued human-made device (Denisenko et al. 2013). Deeper research into known objects in space demonstrated that this object was the latter, viz., the upper stage of a rocket that had launched a space-based radio telescope into an unusual orbit (Denisenko & Lipunov 2013). In this case, D suggested artificial origin, and the uncatalogued status of the object at the beginning meant that C initially included some possibility that it was extraterrestrial, but later C was refined by subsequent analysis to eliminate that scenario.

Provided that C is adequately detailed (e.g., garnered through extensive in situ observations), the false positives for artifact technosignatures should be markedly low after an Earth-based origin has been first ruled out. We can choose the fiducial value of $\xi \sim 10^4$ to indicate a very high confidence in the detection of such technosignatures. This is the same value introduced for electromagnetic technosignatures (and CFCs) although the magnitude of ξ might perhaps be even greater as the false positives for certain physical artifacts may be lower than some other classes of technosignatures.

If the available contextual information is ample, it may follow that $P(T|C)$ is enhanced although this trend is by no means assured. The rationale is that the contextual information (i.e., not the actual data itself) might help constrain the set of alternative hypotheses and boost $P(T|C)$, the latter of which translates to an increased posterior. However, we emphasize that the domain of artifact technosignatures remains poorly explored and characterized, owing to which the preceding tentative surmises must be interpreted with due caution.

4. Alternatives to the Bayesian Framework

Throughout the course of Section 3, we have underscored the relevance of the prior $P(T|C)$, as well as the difficulty of estimating this probability in a particular context (Kiang et al. 2018). Instead, if we could identify alternative frameworks that bypass the need to explicitly (albeit not implicitly) specify the prior, they may accordingly enable us to circumvent, at least partially to some degree, one of the central obstacles outlined here. To actualize the major objective of this work, such formulations should have the capacity to differentiate between promising and dubious technosignature candidates. Studies that touch on alternatives include Popper (1959), Smithson (1989), Halpern (2017), and Sprenger & Hartmann (2019). It can be readily appreciated that this domain is vast and would warrant a solo treatment. Hence, we choose to focus on only a single method and comment briefly on other possibilities for future research.

The formalism that we shall delve into hereafter is known as Signal Detection Theory (SDT), which witnessed substantial developments in the mid-twentieth century (Peterson et al. 1954; Tanner & Swets 1954; Marcum 1960; Green & Swets 1966). Reviews of SDT can be found in Green & Swets (1966), Egan (1975), Wickens (2002), McNicol (2005), Schonhoff & Giordano (2006), and Swets (2014). In broad terms, SDT is concerned with decision-making in the presence of uncertainty and seeks to ascertain the probability that a given input (namely, the data D) originates from the so-called “signal” (the hypothesis T in our setup). SDT has been employed in fields as diverse as psychology, electrical engineering, ecology, medicine, and meteorology. We emphasize at the outset, however, that SDT should not be construed as being an unqualified “improvement” over the Bayesian formulation or that it is more rigorous or objective in character in comparison to the latter.

The idea of harnessing SDT to gauge the credibility of electromagnetic technosignatures was briefly (and qualitatively) broached in McCarley & Benjamin (2013, p. 470), who posed the following question and intimated that it could be resolved by utilizing SDT.

How likely is it that a given evidence sample is consistent with the presence of a signal—a message from aliens, a cancerous tumor, a camouflaged gun, a fatigued pilot—rather than from noise or some other specified alternative?

Subsequently, Pohorille & Sokolowska (2020) highlighted SDT as a means of evaluating whether potential biosignatures are caused by extraterrestrial biology.

Ideally, we require a metric—loosely fulfilling a similar function as the posterior probability $P(T|D, C)$ —that enables us to quantify the degree of confidence that D is generated through the action of extraterrestrial technology for a specific context C . We will adopt the Youden index (also known as Youden’s J statistic) proposed in 1950 to study cancer diagnostic tests (Youden 1950). The Youden index J has become one of the cornerstones in estimating accuracy/performance of experiments and models (Glas et al. 2003; Sullivan Pepe 2003; Ruopp et al. 2008; Šimundić 2009; Swets 2014). By drawing on the standard definition of J (Youden 1950) and adapting it for our area of inquiry, we duly

introduce (see Pohorille & Sokolowska 2020)

$$J = P(D|C, T) - P(D|C, \bar{T}). \quad (9)$$

A high value of J is emblematic of the technosignature candidate being reliable, and the converse also holds true.

Circling back to Equation (9), it is not feasible to express the Youden index J purely as a function of variables delineated earlier (namely, $P(T|C)$ and ξ) because all we know is that $0 \leq P(D|C, T) + P(D|C, \bar{T}) \leq 2$. However, under certain circumstances, $P(D|C, T) + P(D|C, \bar{T}) \sim 1$ might be applicable. This scenario conveys that if the likelihood of D stemming from extraterrestrial technology is high, then the likelihood of D originating from nontechnological sources is low and vice versa. This situation is *not* necessarily valid,¹⁴ but we pursue it because additional simplification is achievable as illustrated below. On invoking $P(D|C, T) + P(D|C, \bar{T}) \sim 1$ along with Equation (5), we find that Equation (9) is expressible as

$$J \sim \frac{\xi - 1}{\xi + 1}. \quad (10)$$

Owing to the fact that $0 < \xi < \infty$, it is straightforward to verify that $-1 < J < 1$, which preserves the general property of the Youden index, and that the upper bound is attained when $\xi \rightarrow \infty$. A higher value of J is tantamount to greater confidence that D is attributable to extraterrestrial technology for particular C .

Equipped with the equation for J in Equation (10), we will revisit electromagnetic technosignatures and atmospheric technosignatures explicated in Sections 3.2 and 3.3, respectively. Our exposition will be brief since we have already covered these topics in some depth earlier.

1. *Electromagnetic technosignatures:* Artificial electromagnetic signals transmitted by ETIs have an extremely low risk of false positives if sufficient contextual information is available. As described in Section 3.2, it is reasonable to work with ξ that is orders of magnitude higher than unity such as $\xi \sim 10^4$. On substitution into Equation (10), we obtain $J \approx 1$, indicating that electromagnetic technosignatures can score highly on the Youden index.
2. *Nitrogen oxides as atmospheric technosignatures:* As elucidated in Section 3.3, NO_x on Earth is characterized by $\xi \sim 3$ although it is essential to recognize that ξ could be much higher or lower on other worlds. We arrive at $J \sim 0.5$ after invoking Equation (10), which appears to suggest that NO_x is not a particularly strong technosignature on Earth and its exact analogs; however, J may be much enhanced for NO_x manufactured on service worlds.
3. *CFCs as atmospheric technosignatures:* Unlike NO_x , CFCs on Earth do not have known nonanthropogenic sources, implying that $\xi \gg 1$. Hence, on selecting $\xi \sim 10^4$ and plugging this value into Equation (10), we obtain $J \approx 1$. Therefore, along similar lines as electromagnetic technosignatures, CFCs can perform extremely well on the Youden index although the accompanying caveat is

that unknown nontechnological pathways to synthesize CFCs might exist elsewhere.

4. *Artifact technosignatures:* Given sufficient context that enables us to rule out an Earth-based provenance at high confidence, it is plausible that artifact technosignatures may also attain very high ξ values. On selecting $\xi \approx 10^4$, as we have done in Section 3.4, we again arrive at $J \approx 1$. Thus, artifact technosignatures can score highly on the Youden index if the contextual information is adequate to discount Earth-based origins.

Before moving on, we caution that SDT and the Youden index have their share of limitations, which are reviewed in several publications (Wickens 2002; McNicol 2005; Ruopp et al. 2008; Steyerberg et al. 2010; Liu et al. 2011). For example, Equation (9) is constructed under the postulate that the sensitivity and specificity are accorded equal weight (Glas et al. 2003); if this assumption is generalized to encompass arbitrary weights, then J must be modified. Furthermore, if the priors happen to be tightly constrained for a given system, the Bayesian framework is preferable from a formal standpoint.

We round off this section by sketching alternative avenues that may aid us in assessing the veracity of technosignature candidates. In the domain of performance/diagnostic accuracy tests, multiple metrics such as the positive and negative predictive values are prevalent (Šimundić 2009). On translating three of the expressions in Glas et al. (2003) to the notation employed in this work, we end up with

$$\mathcal{L}_+ = \frac{P(D|C, T)}{P(D|C, \bar{T})} = \xi, \quad (11)$$

$$\mathcal{L}_- = \frac{1 - P(D|C, T)}{1 - P(D|C, \bar{T})} \sim \frac{1}{\xi}, \quad (12)$$

$$\mathcal{OR} = \frac{\mathcal{L}_+}{\mathcal{L}_-} \sim \xi^2, \quad (13)$$

where the second equality in Equation (11) directly follows from Equation (5). In contrast, the second equality in Equations (12) and (13) is valid only if the extra proviso in the paragraph below Equation (9) holds true. $\mathcal{L}_+$ is called the positive likelihood ratio and represents the ratio of the probabilities that the data D are produced when extraterrestrial technology is existent and absent, respectively. $\mathcal{L}_-$ is known as the negative likelihood ratio, which possesses the same definition as $\mathcal{L}_+$, except that we focus on D *not* being generated in this instance. Lastly, the diagnostic odds ratio $\mathcal{OR}$ can be interpreted as the ratio of the odds of D being manifested in the presence and absence of extraterrestrial technology, respectively.

Since Equations (11), (12), and (13) are solely dependent on ξ (which loosely embodies the odds of false positives), albeit only in certain situations, it is straightforward to estimate the corresponding likelihood ratios and the diagnostic odds ratio for electromagnetic, atmospheric, and artifact technosignatures as we have previously quantified ξ for this trio of classes. High values of $\mathcal{L}_+$ and $\mathcal{OR}$ and low magnitudes of $\mathcal{L}_-$ would suggest that the associated technosignature candidates are credible.

5. Conclusion

In astrobiology, the Bayesian framework has emerged to the forefront with respect to gauging the viability of biosignatures

¹⁴ It is theoretically possible for the signal D to be produced with high probability by both extraterrestrial technology and nontechnological pathways, in which case one may have $P(D|C, T) + P(D|C, \bar{T}) > 1$. Concrete examples of this kind are poorly characterized and cannot be dismissed outright.

and has consequently engendered some crucial questions in its wake relating to false positives and priors. Likewise, when confronted by a putative technosignature, it is necessary to ascertain the probability that it was genuinely created by extraterrestrial technology. In this paper, we examine the key question of what constitutes a robust technosignature by means of Bayesian and non-Bayesian paradigms.

By mirroring the approach espoused in Catling et al. (2018) and proceeding in a similar vein as Walker et al. (2018), we outlined a simplified Bayesian framework in Section 2. Our analysis herein suggests that compelling technosignatures typically evince $P(T|C)\xi \gtrsim 1$, where $P(T|C)$ is the prior probability for the existence of specific extraterrestrial technology in a given context C , and ξ is a measure of false positives associated with the garnered data D for particular context C . In agreement with preceding studies on biosignatures, in Section 3.1 we conclude that an ideal technosignature must not only have markedly low odds of false positives (i.e., preferably $\xi \gg 1$) but also be associated with a high prior.

In Sections 3.2, 3.3, and 3.4, we respectively explored the ramifications of the Bayesian model for electromagnetic (e.g., artificial radio signals), atmospheric (e.g., CFCs), and artifact technosignature candidates, respectively. We demonstrated that electromagnetic signals, CFCs, and artifacts are ostensibly characterized by $\xi \gg 1$, thereby rendering them plausible technosignature candidates, whereas nitrogen oxides may have $\xi \sim 1$, indicating that their credentials are not as strong. However, even in the most optimistic cases with ξ being many orders of magnitude greater than unity, we showed that a sufficiently small prior, which could be applicable in some specific instances, can diminish the reliability of prospective technosignatures.

However, determining the magnitude of the prior is no mean task even with contextual information, and a similar drawback can arise from the potential existence of “unconceived alternatives” (Stanford 2006). For this reason, seeking out and utilizing alternative diagnostics that do not depend explicitly on the prior could, perhaps, complement and supplement the Bayesian method, which we tackle in Section 4. It must, however, be recognized that such formulations do not strictly overcome the challenges posed by priors and unconceived alternatives and cannot therefore be interpreted as being more objective or rigorous. Instead, it is more appropriate to envisage them as parallel methods for assessing technosignature candidates. Future work is necessary for gauging whether SDT, the method delineated in Section 4, may shed some additional light on this topic and determining what its pros and cons would be relative to the Bayesian formalism.

We propose that metrics used in tests of diagnostic accuracy might be gainfully harnessed to investigate technosignature candidates. Some of them, such as the positive likelihood ratio (which is equivalent to ξ), can already be crudely computed for select technosignature candidates (e.g., atmospheric gases) by current models. Other diagnostics (so to speak), such as the well-known Youden index, could be determined likewise under certain (albeit not general) circumstances. In congruence with the Bayesian model, we find that electromagnetic signals, CFCs, and artifacts might be relatively well suited as potential technosignatures (more so than nitrogen oxides) due to their high values of ξ .

This work does not claim to be definitive or exhaustive in scope. Several avenues for future research are conceivable, such as generalizing binary hypotheses to allow for multiple outcomes and identifying appropriate metrics for assessing putative technosignatures. Nonetheless, in view of the encouraging progress accomplished by technosignature science in the past few years, we hope that the paper begins to lay the groundwork for developing a systematic methodology to gauge the robustness of future technosignature candidates.

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