Detection of Extrasolar Navigation Beacons

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Abstract

It is shown that a hypothetical interplanetary navigation system in operation around another star might be detectable with appropriate signal processing techniques. Under the condition that the Earth is roughly in the ecliptic plane of the star under consideration, navigation beacons might be detectable over hundreds of light years, by searching peaks in the autocorrelation function of an extensive set of samples in the microwave band. The autocorrelation method used is briefly discussed, a consistent set of link parameters related to the speculative navigation beacons is derived, and some simulation results are shown.

1. Introduction

Most SETI searches, all-sky surveys as well as targeted searches, have so far mainly focused on detection of deliberately transmitted beacon signals such as CW (Continuous Wave) signals or pulsed waveforms. The main motivations for this choice are that this kind of signals are as simple as possible, that they could be clearly identified as being from an artificial origin, and that the link budget considerations are supposed to be favourable. However, the assumption of ETI setting up and transmitting such beacon signals deliberately is an important a priori condition for these searches.

In this paper we try to perform a short (and incomplete) analysis of the detectability of other, rather wideband type of signals which could be part of the regular communications environment of an ETI.

Some authors have argued that the normal communication links of ETI are undetectable, because an advanced civilization will naturally evolve to the most efficient possible modulation formats and air interfaces schemes. And hence such communication links would not only be undetectable beyond their intended operational area, but to an external eavesdropper they would even be undistinguishable from noise [1]. However, such reasoning has only limited validity for the following reasons:

- Communication links can only be set up after a synchronization phase, which should be as straightforward as possible, and hence non-noise like;
- Certain communication waveforms such as those used in satellite navigation are used for measuring distances and hence can't be optimized in the sense explained in [1].

Let's discuss a few examples to illustrate this. 3G communication schemes, such as UMTS/FDD, are using spread spectrum techniques for increased efficiency and flexibility. However, significant power is present in the synchronization channel, broadcast by the base stations, to allow handsets to get connected in the network. This synchronization channel can be detected using autocorrelation, without prior knowledge of the waveform details.

In satellite navigation, the GPS system is now present for more than 30 years. Currently a new satellite navigation system, called Galileo, is under development in Europe. It can be expected that its lifetime will also be over 30 years. Both GPS and Galileo waveforms are using direct sequence spread spectrum, and are detectable using autocorrelation. This means that over a pretty long time window of our radio existence (say 60 out of 100 years), signals are and will be detectable with autocorrelation techniques. Alternative schemes for long-range navigation could be considered using microwave pulses (UWB, or Ultra Wideband) or optical pulses. These are again detectable with correlators, despite the noise-like properties of these signals.

2. Navigation beacons hypotheses

It has been suggested that ETI could place navigation beacons at several positions in their stellar system, for supporting navigation of spacecraft travelling throughout their planetary system [2]. We can assume that in that case, most of the travel would take place in the ecliptic plane of that star, and that hence the navigation beams would also be directed primarily in that plane. This means that, if Earth happens to be in the ecliptic plane of that star, the navigation beams might also occasionally be in our direction. This is illustrated in *Fig. 1*.

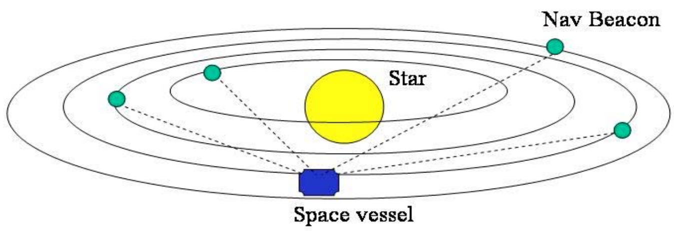

Fig. 1: Navigation beacons in exoplanetary system

Extrasolar planetary systems for which that geometrical condition is valid, include those with exoplanets that have been discovered using the transit technique (through photometry) [3]. This includes stars such as HD 2094586, HD 189733 and TrES-1.

Stars to be selected for a search for navigation beacons (and other communication waveforms which can be detected through autocorrelation) could be taken from the list of exoplanets detected through the transit observation technique. Another strategy could be to target vast amounts of stars all at once, e.g. galactic clusters, as statistically a fair amount of stars will fulfil the geometric condition mentioned above.

3. Detection through autocorrelation

We assume one of the following waveform hypotheses to be valid:

a. A DSSS (Direct Sequence Spread Spectrum) type of waveform with a certain repetition rate, at microwave frequencies (between 1 GHz and several 10's of GHz);
b. An ultra-wideband type of repetitive pulse train, at microwave frequencies;
c. A repetitive optical pulse train.

For the derivations in the rest of this section, we assume the signal is a block wave with an amplitude of 1, and the noise is AWGN (Additive White Gaussian Noise) with standard deviation σ and hence power σ^2. Suppose we have sampled a signal *x* with useful signal content *s* and a noise component *n*. Let *i* be the sample index.

$$x(i) = s(i) + n(i) \qquad (1)$$

If *P* denotes the time lag and *M* the number of samples considered, then we get as autocorrelation result for time lag P:

$$\sum_{i=1}^{M} x(i).x(i+P) \qquad (2)$$

Substituting (2) in (1) yields:

$$\sum_{i=1}^{M} \left[s(i).s(i+P) + s(i).n(i+P) + n(i).s(i+P) + n(i).n(i+P) \right] \qquad (3)$$

Suppose now we have the typical case that the noise power is exceeding the signal power with several orders of magnitude. In the summation (3), the first term is the coherent accumulation of signal contributions. The second and third terms are Gaussian distributed noise terms. The last term is non-Gaussian, but a good approximation is to consider it as a noise component with standard deviation σ^2. Given our assumption of a very negative S/N, this means that the fourth term is dominant. In the case that the investigated time lag P matches the repetition period of the beacon signal, and ignoring here for a while Doppler and other channel effects, we can say that in (3) the useful power will scale as M^2, while the noise power will scale as M σ^4.

This squaring of the noise *power* by the autocorrelation function is a huge penalty. It means e.g. that if the signal level is 20 dB below the noise level, applying (3) will result in the signal level (on average in each term of the autocorrelation) being 40 dB down the noise level in the autocorrelation expression. This spectacular growth in noise power must be overcome by the processing gain of the correlation process, i.e. the first term in (3). This is similar to the increasing processing gain of an FFT with increasing number of samples (in the absence of drift, or with a compensating drift hypothesis) [4].

Doppler effects have a rather limited impact on the correlation processing compared to FFT processing. A constant Doppler shift will result in a phase difference of the samples with lag difference P. A linear Doppler rate (frequency changing linearly over time) results in a fixed frequency difference between the samples with lag difference P. This must be compensated for by introducing a factor in (2) that represents the frequency shift as a function of the Doppler rate.

E.g., if the frequency is equal to

$$\omega + \rho t \tag{4}$$

with ρ being the Doppler rate, then we have a compensation factor of the form

$$e^{j\,[\rho\, i\, P\, +\, \frac{1}{2}\,\rho\, PP\, +\, \omega\, P]} \tag{5}$$

with ρP being the compensation frequency. Note that the terms of constant phase are not a concern if we consider all factors in the above expressions to be in the complex domain. In [5] the situation for multiplying signals with lagged versions of their own is elaborated for the case of sinusoidal signals.

4. Link budget considerations

The detectability of such navigation beacons over interstellar distances is of course only possible if the link can be closed with appropriate link budget parameters. In the next table, an example is given. The SETI Range Calculator tool, available on the Web [6], has been used.

Navigation beacon Tx frequency	10 GHz
Beacon antenna diameter	100 m
Beacon antenna gain	78 dBi
Beacon transmit power	2 MW
Beacon transmit EIRP	141 dBW
Rx antenna diameter	305 m
Rx system noise Temperature	50 K
Rx antenna gain	88 dBi
Rx antenna G/T	71 dB/K
Bandwidth	1 MHz
Required overall C/N	-35 dB
Path loss	416 dB
Range	165 light years

Table 1: Example link budget

The assumed navigation beacon carrier frequency has been chosen somewhat higher than typical satellite and long distance carrier frequencies, in line with current trends. A difficult point is the antenna gain: high gain antennas give high directivity. This means that we have to assume that navigation beacon signals are more or less pointed to those areas were space vessels are expected. The beacon transmit power has been assumed to be a fairly low 2 MW, together with a high gain antenna. The EIRP of 141 dB has been obtained as follows: we assume that the operational zone of the extrasolar navigation system extends to 10 AU around the host star. This results in a path loss at the edge of the zone of 296 dB. Let’s assume that we want to have a similar C/N at the edge of this zone as we would have for GPS here on earth. GPS satellites have an EIRP transmission of 500 W (27 dBW) and the distance to the GPS satellites results in a 182.8 dB path loss. Hence we need an EIRP of 27 + 296 – 182.8 ≈

141 dBW. Any meaningful combination of transmit power and antenna size (directivity) that leads to this EIRP is acceptable. In [2], a beacon transmit power of 200 MW is suggested.

At the receive side, a number of parameters representative for an Arecibo-like receiving station have been assumed. The rationale for the required Carrier to Noise ratio (C/N) is as follows: the -35 dB C/N will actually result in a -70 dB situation because of the 4^{th} term in (3). With a (truncated) bandwidth of 1 MHz, 1 Msamples/s and 1 sample/code bit, we get 60 dB of processing gain per second coherent integration through the autocorrelation process of expression (3). After 100 seconds, this has grown to 80 dB. This means that after 100 seconds of coherent integration, a S/N (Signal to Noise ratio) of +10 dB can be reached (ignoring channel fading and Doppler effects). Further averaging of the noise power can be done by subsequent non-coherent accumulations or averaging, as described in [7] [8].

Doppler effects will degrade the S/N, although the effect will be much smaller than in the case of large FFTs, because the time lag P can be expected to be relatively small. Fading effects from the ISM (Interstellar Medium) are also important [9] [10], but these are not considered in this basic paper.

Furthermore, it has been assumed that the natural radio interference from the host star in the microwave band of interest is negligible.

5. Simulation setup

In order to illustrate the principles given above, a simple simulation model has been generated in MATLAB. *Fig. 2* shows the simulation setup: A generator block produces a periodic signal with a relatively wide bandwidth, simulating a hypothetical beacon signal. For this waveform, we have taken an m-sequence (*Fig. 3*). This can be represented as a LFSR (Linear Feedback Shift Register) with a number of exor's. When the registers (D-elements in *Fig. 3*) are initially loaded with arbitrary bits (except all-zero), and their values are shifted to the next stage at every clock tick, the output *out* will produce a bit pattern that is periodic with period $2^n - 1$, with n equal to the number of register elements. In *Fig. 3*, we have $n = 13$. M-sequences are also used in de waveform definitions of the GPS and Galileo navigation systems.

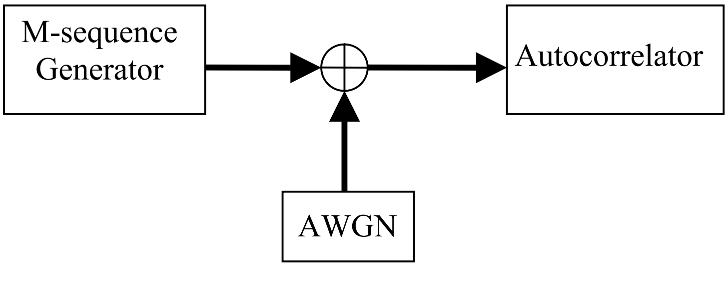

Fig. 2: Simulation setup

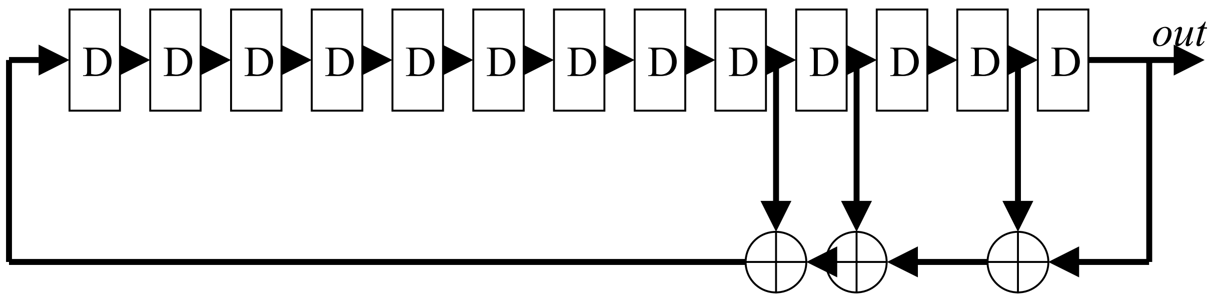

Fig. 3: M-sequence generator example

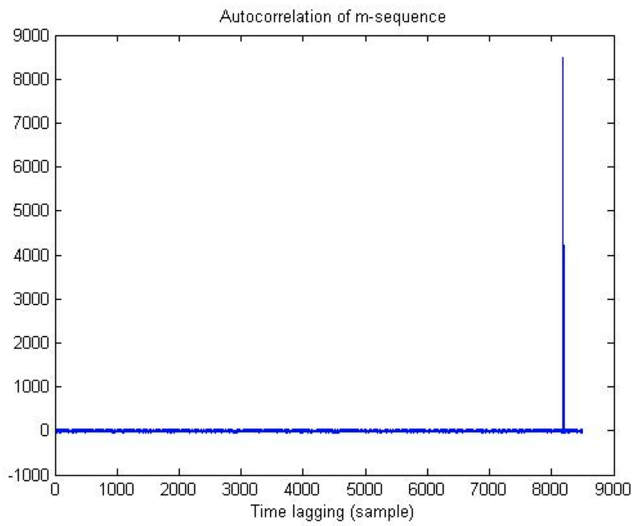

Fig. 4: Autocorrelation in the absence of noise

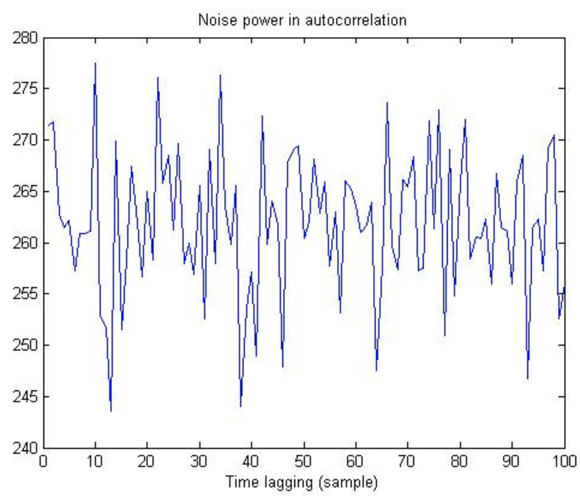

Fig. 5: Average noise power at each lag P

Fig. 4 shows the result of an autocorrelation in the absence of noise. *Fig. 5* shows the average noise power at each lag time P for $\sigma = 4$. The expected mean with value $\sigma^4 = 256$ shows up clearly.

Fig. 6 shows the autocorrelation plot for a signal + noise combination with as parameters:

M-sequence Period	$8{,}191 = 2^{13} - 1$
Noise standard deviation	$\sigma = 4$
Number of samples	20,000
Number of accumulations	$M = 8{,}500$
Max. investigated time lag	$P = 8{,}500$

Table 2: Simulation parameters

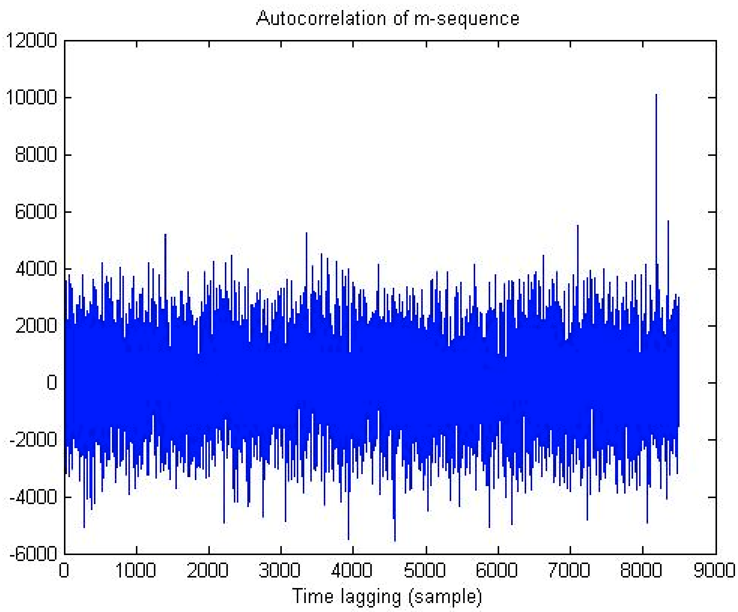

Fig. 6: Resulting autocorrelation profile with the parameters of Table 1.

The autocorrelation's peak value can be distinguished clearly from the noise background. However, the processing gain (accumulation points) required to get this discrimination is rather high: it corresponds to a S/N after correlation of $8{,}500^2$ / 256 or about 30 dB. This requirement can be mitigated by performing additional non-coherent accumulations, as mentioned above. This non-coherent accumulation process could also be extended with calculating hypotheses on adjacent time bins, in order to account for drift resulting from Doppler rates.

6. Conclusion

It is in principle possible to detect the presence of leakage signals from navigation beacons in extrasolar planetary systems, if the signal waveform exploits some kind of periodicity. Details of the beacon signal structure are not required in the hypothesis. The autocorrelation processing is quite computing intensive because a large processing gain has to be realized due to the noise sensitivity of the algorithm. On the other hand, the algorithm is less sensitive to

Doppler effects than the classical FFT processing. More theoretical work as well as more simulations are needed in order to figure out the details and to include other effects such as ISM fading.

Acknowledgements

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References

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