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Interstellar laser communication: implementability criterion and optimisation conditions for the addressed signal search and sending

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Abstract. **Using new opportunities offered by the construction of large optical telescopes, a laser radiation receiver with an iodine active quantum filter, high-energy iodine lasers with a diffraction-limited beam divergence and the discovery of exoplanets of the Earth type, including those located relatively not far from the Sun, we analyse the implementability of interstellar laser communication under the conditions, when the central spot of the diffraction pattern at the place of the laser signal reception by means of large optical telescopes can be made smaller than the orbit of the planet, and the signals come to the specified point of the orbit not synchronously with the planet motion because of the error in the determination of the distance between the Sun and the star, around which the planet chosen for communication rotates.**

Keywords: *interstellar laser communication, large optical telescopes, exoplanets, extraterrestrial civilisations, iodine laser, active quantum filter.*

1. Introduction

At present the active search for exoplanets is being continued [1] and the planets of the Earth type are already revealed, where, in principle, life can exist, including, possibly, the intelligent one. In this connection, the 'addressed' search for the signals from extraterrestrial civilisations (ETCs), i.e., the search for the signals in the radiation of the stars having exoplanets of the Earth type, acquires more and more relevance within the programmes SETI (Search for Extraterrestrial Intelligence) [2], METI (Message for Extraterrestrial Intelligence) [3], and the prospective programme CETI (Communication with Extraterrestrial Intelligence). Below we assume that if an ETC exists at a certain exoplanet, the level of its technological development is at least as high as that of the Earth civilisation.

Due to the construction of large, 10-metre optical telescopes, in which the atmospheric resolution barrier is overcome using adaptive optical systems [4], and the development of many high-energy lasers [5], the electromagnetic waves of the optical range seem to be most suitable for solving the problem of addressed search. The interest in the search for ETC signals in the optical range after the boom related to the MANIA project (Multichannel Analysis of Nanosecond Luminance Variations) [6] and the subsequent fall now began to revive again. To the opinion of Geoffrey Marcy, a distinguished astronomer, who took part in the discovery of 110 exoplanets, including the first discovered system, and who headed the SETI Institute a few years ago, the search for ETCs requires reorganisation. Firstly, it implies the turn towards the optical wavelength range [7], which is confirmed by recent publications [8, 9].

The authors of Refs [10–16] demonstrate the amazing opportunities offered by the use of iodine photodissociation lasers for solving the problems related to the search for signals from ETCs, as well as to sending the signals to them. First, this is due to the appearance of a narrow-band active quantum filter (AQF) based on the iodine photodissociation amplifier (the wavelength $\lambda = 1.315$ μm). This filter has a gain line, rigidly fixed in its spectral position, with a width smaller than 0.01 cm^{-1} (the resolution $\lambda/\Delta\lambda > 7.6\times10^5$) and the quantum limit of sensitivity [17], which makes it possible to detect, select and record laser signals consisting of a few photons against the background of the studied star radiation [18]. Second, at $\lambda = 1.315$ μm the high-power nanosecond iodine lasers are created with the diffraction-limited radiation divergence and the pulse energy exceeding 2 kJ [5]. The radiation frequency tuning of these lasers within a few inverse centimetres by means of the magnetic field [19] allows the compensation for Doppler frequency shifts, caused by the relative motion of the transmitter and the receiver along the line connecting them with the velocity, exceeding 200 km s^{-1}. Third, the radiation with $\lambda = 1.315$ μm lies within the atmospheric transparency window and can be received by ground-based optical telescopes.

The consideration of interstellar laser communication implementability in Refs [10–16] and earlier papers [20–24] was based on the assumption that at the location of reception, the centre of the diffraction pattern (DP) of the signal coincides with the detector. This assumption is justified in the case when the central DP spot is much larger than the size of the planet orbit. In the radiofrequency range, this is always true.

In the optical-range studies of stars using large optical telescopes, it is sometimes possible to see directly the planets rotating around the stars. Thus, for example, the first direct photograph of an exoplanet (near the star 2M1207 in the Centaurus Constellation) was obtained using the 8-metre VLT telescope as long ago as 2004 [4]. In 2014, the erection of the E-ELT telescope with the main mirror diameter of almost 40 m was started [25]. The main goal of the E-ELT observatory team will be a thorough study of the known exoplanets and the discovery of new ones. The OWL (overwhelmingly large telescope) telescope with the main mirror diameter 100 m is also under development [26].

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Hence, if using such telescopes the laser signals are sent to exoplanets, particularly those relatively not far from the Sun, or when the signals are sent to the Earth by the ETCs populating these exoplanets, the DP diameter at the receiver location may appear comparable with the orbit diameter of the receiver-carrying planet, or even smaller than this diameter. Although the related questions have been raised long ago (see Ref. [2]), the answers to them did not allow for the uncertainty of the planet position at the time of the signal arrival at the aimed segment of the orbit, caused by the error of determining the interstellar distances. Therefore, the earlier considered criteria of interstellar communication implementability, based on the assumption that the detector is in the DP centre, are not applicable for answering practically important questions, related to the parameters of transceiver devices. The goal of the present paper is to find a criterion of implementability of interstellar laser communication under the conditions described above.

2. Basic relations

Let the ETC transmit a laser beam at the wavelength λ towards the Sun (or our civilization sends a signal towards the star with an exoplanet suitable for life) with the plane wave front, the circular cros section with the diameter D_{b} and the energy of each pulse E uniformly distributed over the beam cross section. In the far-field zone, such a beam forms a DP, in which the radiation intensity is described by the widely known Airy formula [27]. For our purposes, let us write it in the form

$$I(r) = \frac{ER^2}{4\pi r_0^2}\left(2\frac{J_1(r/r_0)}{r/r_0}\right)^2, \tag{1}$$

where $r_0 = \lambda R/\pi D_{\mathrm{b}}$; R is the distance from the transmitter; $r \ll R$ is the distance from the DP centre to the receiver; and $J_1(x)$ is the first-order Bessel function of the first kind.

As mentioned in the Introduction, the consideration of earlier papers was based on the assumption that for the interstellar distances the central spot of the DP is much larger than the planet orbit. Then, if the signal is sent towards the Sun or the star with a hypothetic ETC, one can consider the receiver-carrying planet to be located practically in the centre of the DP. Then the function $J_1(x)$ can be expanded in a Taylor series with only the first-order term taken into account. Then the intensity of radiation at the reception point is expressed as $I(r) = EA_{\mathrm{b}}/\lambda^2$, where $A_{\mathrm{b}} = \pi D_{\mathrm{b}}^2/4$ is the area of the beam cross section, and the expression for the received energy for the receiver aperture A_{r} is $E_{\mathrm{r}} = I(r)A_{\mathrm{r}}/R^2 = EA_{\mathrm{b}}A_{\mathrm{r}}/(\lambda^2R^2)$. The latter expression is used in the papers [10–16, 20–24], mentioned above.

When the planet with the receiver is sufficiently far from the DP centre, we cannot restrict ourselves to the linear term of the Taylor expansion of $J_1(x)$. Then, with the atmosphere transmission of the Earth T_{E} and the exoplanet T_{e} taken into account, the energy received by the telescope with the diameter D_{r} of the circular aperture should be described by the expression

$$E_{\mathrm{r}} = I(r)A_{\mathrm{r}}/R^2 = ET_{\mathrm{E}}T_{\mathrm{e}}(D_{\mathrm{r}}/2r)^2J_1^2(D_{\mathrm{b}}/D_0), \tag{2}$$

where $D_{\mathrm{b}}/D_0 \equiv r/r_0$, and $D_0 = \lambda R/\pi r$. If λ and D_0 are expressed in metres, R in parsecs (pc), and r in the astronomic units (a.u.), then $D_0 = 8.63\times10^{-2}R/r$. From Eqn (2) with the properties of $J_1(x)$ taken into account one can see that with an increase in D_{b} starting from zero, the energy E_{r} at first grows, then falls to zero and then experiences damping oscillations with alternating maxima and zeros. From the practical point of view, the interesting region of the argument values for the function $J_1(x)$ is the region near its first and largest maximum, i.e. $0 \leqslant x \leqslant 3.83$. The value $x = x_0 \approx 3.83$ corresponds to the first dark ring of the DP, and the maximal value of $J_1(x)$ is achieved at $x = x_{\mathrm{m}} = 1.84$.

3. Criterion of implementability of interstellar laser communication

If the signal within the telescope aperture is detected using a device with the sensitivity S_μ, which is the minimal energy that can be detected by the receiver having the signal-to-noise ratio μ with the probability exceeding $1-\mu^{-2}$, then the necessary condition is $E_{\mathrm{r}} \geqslant S_\mu$. Hence, with Eqn (2) taken into account, we obtain the criterion of the interstellar laser communication implementability, when the dimensions of the DP central spot and the orbit of the planet are in arbitrary relation, and the planet itself is located at a distance r from the centre of DP:

$$\frac{D_{\mathrm{r}}\sqrt{ET_{\mathrm{E}}T_{\mathrm{e}}}}{r} \geqslant \frac{2\sqrt{S_\mu}}{J_1(D_{\mathrm{b}}/D_0)}. \tag{3}$$

The laser receiving system with the iodine AQF at $\mu = 3$ has the sensitivity $S_\mu = 3\hbar\omega = 4.53\times10^{-19}$ J, where $\hbar\omega = 1.51\times10^{-19}$ J is the energy of the laser radiation quantum with the wavelength $\lambda = 1.315$ μm. Then, expressing r is astronomic units, E in joules, and D_{r} in metres we can transform the criterion to the form more convenient for use

$$\frac{D_{\mathrm{r}}\sqrt{ET_{\mathrm{E}}T_{\mathrm{e}}}}{r} \geqslant \frac{201}{J_1(D_{\mathrm{b}}/D_0)}. \tag{4}$$

From Fig. 1 one can see that with an increase in the beam diameter starting from zero, the fulfilment of the criterion

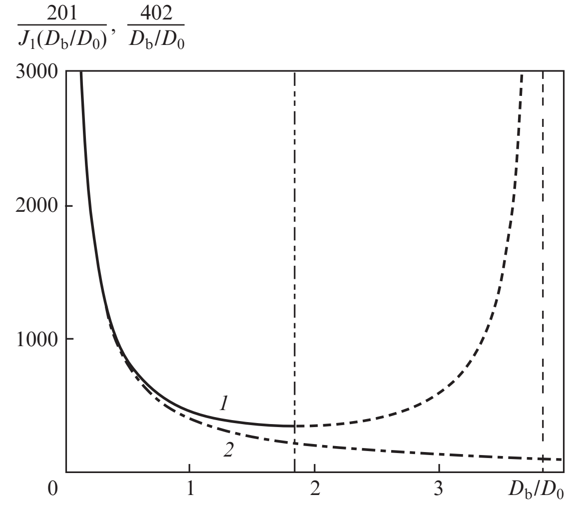

Figure 1. Dependence of the right-hand side of criterion (4) on the ratio D_{b}/D_0 (*1*) and the approximation of the right-hand side of (4) under the assumption that the central DP spot is much larger than the orbit of the planet, $402/(D_{\mathrm{b}}/D_0)$ for $D_{\mathrm{b}}/D_0 < 1/2$ (*2*); the vertical straight line $D_{\mathrm{b}}/D_0 \cong 1.84$ corresponds to the maximum of the Bessel function, and the straight line $D_{\mathrm{b}}/D_0 \cong 3.83$ corresponds to the radius of the first dark ring of the Airy pattern.

becomes easier, since the right-hand side of Eqn (4) decreases and has a minimum at $D_b/D_0 = x_m \cong 1.84$.

4. Optimal regime of interstellar laser communication

At the minimum point of the right-hand side of Eqn (4), criteria (3) and (4) split into two conditions. The first condition is

$$D_b \cong 0.159R/r \tag{5}$$

and, since this value of D_b corresponds to the maximal value of J_1, equal to 0.582, the second condition is

$$D_r\sqrt{ET_E T_e}/r \geqslant 346. \tag{6}$$

The value of D_b (5) corresponds to the optimal beam diameter D_b^{opt}, since in this case the energy E_r is maximal, as follows from Eqn (2). Since the beams of light are formed by telescopic systems, the diameter of the main mirror of the transmitting telescope $D_t = D_b$, so that D_b^{opt} determines the optimal diameter of this mirror $D_t^{opt} = D_b^{opt}$.

From the above considerations, it is clear that the choice of D_t^{opt} for each particular exoplanet requires the determination of the maximal distance from the DP centre, at which the exoplanet may be randomly found at the time of the signal arrival.

4.1. Estimation of the maximal distance between the planet and the diffraction pattern centre at the time of signal arrival

Since the exoplanet orbit parameters can be determined with rather high accuracy, for the sufficiently large D_t it is possible to aim the radiation not merely at the star, around which the observed planet rotates, but at any segment of its orbit. This is implementable, since in the telescope focus one can adjust the relative position of the DP of the star radiation and the DP formed by the source of the sent signal with the accuracy achieving the tenths of the radius of the first dark ring [28], providing the beam aiming with the error much smaller than its divergence. However, as mentioned before, the error in the determination of interstellar distances makes it impossible to synchronise exactly the signal arrival at the given place of the orbit with the passage of this place by the planet. Let us estimate the maximal distance from the DP centre, at which the planet may find itself at the time of the signal arrival. Consider two limiting cases of the planet orbit orientation with respect to the observation line, which enclose all other particular cases:

1. The plane of the orbit is perpendicular to the observation line. For the eccentricity $e < 0.44$ the orbit looks practically as a circle.
2. The orbit plane is oriented so that the observation line lies in it; then the orbit looks as a segment of a straight line.

Apart from the systematic displacement of the frequency, caused by the relative motion of stars, in the first case only the transverse Doppler effect takes place, the appropriate frequency deviation being insignificant as compared to the AQF gain linewidth. Hence, for the matching of the transmitter radiation spectrum with the spectral band of the receiver there is no difference, which part of the planet orbit the telescope is to be aimed at. The distance between the receiver and the DP centre at $e < 0.44$ is well approximated by the law $r = 2a|\sin(\pi t/P)|$, where a is the major semiaxis of the orbit, and P is the period of the planet rotation around the star. In the second case for the same e it is reasonable to aim the telescope at the centre of the above-mentioned straight line segment, in which the Doppler effect is also transverse, and the distance between the receiver and the DP centre varies according to the law $r = a|\sin(2\pi t/P)|$.

Let the distance to the observed star be determined with the error δR. The corresponding time error is $\delta R/c$. Since $2|\sin(\pi t/P)| \geqslant |\sin(2\pi t/P)|$, the value of r for other orientations of the orbit lies within the limits

$$a|\sin(2\pi\delta R/cP)| \leqslant r \leqslant 2a|\sin(\pi\delta R/cP)|. \tag{7}$$

From (7) the condition that during the time $\delta R/c$ the planet may find itself at the distance not smaller than a from the DP centre is the inequality $\delta R/P \geqslant c/4$. In this case, the beam aiming at a definite point of the orbit is not reasonable. The simplest decision is to aim the telescope straight at the star. The maximal distance $\bar{r}$ between the planet and DP centre will be equal to a. If δR is expressed in parsecs and the period P in earthdays, then the above inequality takes the form

$$\delta R/P > 2.1\times10^{-4}. \tag{8}$$

The condition that the distance from the DP centre is smaller than a during the time $\delta R/c$ is expressed by the inequality $\delta R/P < c/6$ ($\delta R/P < 1.4\times10^{-4}$ pc day^{-1}). If it is valid, the telescope should be aimed at the centre of the straight-line segment mentioned above. In this case, as follows from Eqn (7), the maximal distance between the receiver and the DP centre is $\bar{r} = 2a|\sin(\pi\delta R/cP)|$. When $2\pi\delta R/cP \ll 1$, we obtain $\bar{r} \cong 2\pi a\delta R/cP$, or

$$\bar{r} \cong 7480a\delta R/P, \tag{9}$$

if δR is expressed in parsecs, a in astronomic units, and P in earthdays.

4.2. Estimation of optimal dimensions of transmitting telescopes for potentially inhabited planets

Let us clarify the validity of the conditions $\delta R/P < 1.4\times10^{-4}$ and $\delta R/P > 2.1\times10^{-4}$ for exoplanets belonging to the class of potentially inhabited ones that are widely discussed in the literature, namely, Kapetyn b, Gliese 667C c, Gliese 581 d, Gliese 581 c, Gliese 581 g, Gliese 163 c, Gliese 832 c, Kepler-22 b, Kepler-69 c, 61 Virginis b, HD 85512 b, and tau Ceti e (the range of distances from 3.6 to 830 pc). In Table 1 their astronomic characteristics are summarised. The errors of the dis-

Table 1. Astronomic characteristics of exoplanets.

Exoplanet	Constellation	R/pc	a (a.u.)	e	P/days
Kapetyn b	Pictor	3.91±0.01	0.168	0.21	49
Gliese 667C c	Scorpio	6.2±0.1	0.12	0	28
Gliese 581 d	Libra	6.2±0.1	0.22	0	67
Gliese 581 c	Libra	6.2±0.1	0.07	0.177	13
Gliese 581 g	Libra	6.25±0.09	0.146	0	37
Gliese 163 c	Dorado	15	0.125	0.1	26
Gliese 832 c	Grus	4.9	0.162	0.03	36
Kepler-22 b	Cygnus	190	0.849	–	290
Kepler-69 c	Cygnus	830	0.64	0.14	242
61 Virginis b	Virgo	8.52±0.05	0.05	0.12	4.21
HD 85512 b	Vela	11.1±0.1	0.26	0.11	54.4
tau Ceti e	Cetus	3.65±0.002	0.552	0.05	168

Table 2. Parameters of interstellar communication implementation in the optimal regime.

Exoplanet	Signals from the exoplanet to the Earth					Signals from the Earth to the exoplanet				
	$\delta R/P$/pc day^{-1}	$\bar{r}$ (a.u.)	D_t^{opt}/m	D_r^{min}/m at $E = 2$ kJ	E/J at $D_r = 10$ m	$\delta R/P$/pc day^{-1}	$\bar{r}$ (a.u.)	D_t^{opt}/m	D_r^{min}/m at $E = 2$ kJ	E/J at $D_r = 10$ m
Kapetyn b	2.7×10^{-5}	0.2	3.1	1.93	75	2.0×10^{-4}	0.168	3.7	1.6	53
Gliese 667C c	2.7×10^{-4}	1.0	0.99	9.7	1.9×10^{3}	3.6×10^{-3}	0.12	8.2	1.2	27
Gliese 581 d	2.7×10^{-4}	1.0	0.99	9.7	1.9×10^{3}	1.5×10^{-3}	0.22	4.5	2.1	90
Gliese 581 c	2.7×10^{-4}	1.0	0.99	9.7	1.9×10^{3}	7.7×10^{-3}	0.07	14	0.68	9
Gliese 581 g	2.5×10^{-4}	1.0	1.0	9.7	1.9×10^{3}	2.5×10^{-3}	0.146	6.8	1.4	40
Gliese 163 c	4.1×10^{-3}	1.0	2.4	9.7	1.9×10^{3}	5.8×10^{-3}	0.125	19	1.2	29
Gliese 832 c	1.3×10^{-3}	1.0	0.78	9.7	1.9×10^{3}	1.4×10^{-2}	0.162	4.8	1.6	49
Kepler-22 b	5.2×10^{-2}	1.0	30	9.7	1.9×10^{3}	6.5×10^{-2}	0.849	36	8.2	1345
Kepler-69 c	2.3×10^{-1}	1.0	130	9.7	1.9×10^{3}	3.4×10^{-1}	0.64	210	6.2	764
61 Virginis b	1.4×10^{-4}	1.0	1.35	9.7	1.9×10^{3}	1.2×10^{-2}	0.05	27	0.48	4.7
HD 85512 b	2.7×10^{-4}	1.0	1.76	9.7	1.9×10^{3}	1.8×10^{-3}	0.26	6.8	2.5	126
tau Ceti e	5.5×10^{-6}	0.041	14	0.4	3.1	1.2×10^{-5}	0.049	12	0.47	4.5

tance from exoplanets to the Sun are assumed the same as for the distances from the Sun to the stars, around which the planets rotate. Where not indicated, the errors are assumed to be 10% [29].

First, we calculated the ratio $\delta R/P$ and the value of $\bar{r}$ for the case, when the signal is sent from an exoplanet and received at the Earth, for which it is known that $a = 1$, $e = 0.017$, $P = 365.256$ days [30]. From Table 2 it is seen that only for two exoplanets, Kapetyn b and tau Ceti e, the equality $\delta R/P < 1.4\times10^{-4}$ pc day^{-1} is valid and the precise aiming of the radiation at the particular parts of the Earth orbit becomes reasonable. It is also seen that except the exoplanets Kepler-22 b, Kepler-69 c, and tau Ceti e, the diameters D_t^{opt} do not exceed those of the telescopes available at the Earth.

A different situation occurs when the signals are sent from the Earth towards the exoplanets. From the data of Table 2, we conclude that only for tau Ceti e the precise aiming at the given segments of the orbit is reasonable. For all the rest planets one has to aim the beam straight at the star about which the planet rotates. It is seen that for implementing the optimal communication a half of the considered exoplanets requires larger telescopes than those existing at the Earth. Obviously, under the condition of more precise determination of interstellar distances these results may change due to the reduction of the uncertainty of the planet position at the orbit at the time of signal arrival. From Table 2 it also follows that except the exoplanet tau Ceti e, the requirements to the dimension of telescopes for sending the signal towards the Sun are less severe than for sending the signals from the Earth to the exoplanets.

4.3. Relations between the dimensions of the receiving telescope and the pulse energy of the sent signals in the optimal communication regime

Thus, let the transmission of the signal be implemented in an optimal way. Then, assuming that the exoplanet atmosphere transmission is similar to that of the Earth, i.e., for the radiation with $\lambda = 1.315$ μm $T_e = T_E > 0.8$ [31], the relation (6) for $r = \bar{r}$ takes the form

$$D_r\sqrt{E}/\bar{r} \geqslant 432. \tag{10}$$

Table 2 presents the minimal acceptable diameters of the receiving telescopes $D_r^{min} = 432\bar{r}/\sqrt{E}$ for receiving the laser pulses with $E = 2$ kJ, as well as the required pulse energies $E = (432\bar{r}/D_r)^2$ for $D_r = 10$ m for sending the signals both from exoplanets to the Earth and from the Earth to exoplanets. Note that for the signal from exoplanets received at the Earth, when at the time of signal arrival $\bar{r}$ is equal to the Earth orbit semiaxis and E amounts to 2 kJ, the diameter $D_r^{min} = 9.7$ m. This result was obtained earlier [11, 14] using other methods. For the exoplanets Kapetun b and tau Ceti e the signal forms the DP smaller than the orbit of the Earth, and the value of D_r^{min} is essentially smaller than 10 m. When the signals are sent from the Earth, the required diameters of the receiving telescopes installed at all exoplanets (Table 2) are essentially smaller than 10 m. We can conclude that, except the tau Ceti e exoplanet, it is easier to detect the signals sent from the Earth than those sent to the Earth from the considered exoplanets.

5. Requirements to the telescope dimensions and laser pulse energies in the nonoptimal regime

From Table 2 it is seen that for six of the twelve considered exoplanets the optimisation conditions for the laser communication can be satisfied using the optical telescope with the main mirror diameter not exceeding the diameter of the main mirrors of the optical telescopes already created at the Earth. For some of these exoplanets, such as Gliese 581 c, Gliese 163 c, Kepler-22 b, Kepler-69 c, 61 Virginis b, tau Ceti e, the diameters of the main mirrors required for the optimal interstellar communication appeared to be larger than the diameters of the existing terrestrial telescopes. Thus, with these exoplanets it is yet impossible to establish two-side communication, operating in the optimal regime. Naturally, the question arises with which of the listed exoplanets it is still possible to establish the communication using the systems, analogous to the ones created at the Earth, and with which it is currently impossible.

The criterion proposed in the present paper allows the answer to this question. The astronomic data, based on which the calculations were performed, the ratio $\delta R/P$, and the values of $\bar{r}$ are presented in Tables 1, 2. From these data, as mentioned above, it follows that among the six chosen exoplanets only for the exoplanet tau Ceti e it is reasonable to aim the signal radiation at a particular place of the Earth orbit, since only for this planet $\delta R/P < 1.4\times10^{-4}$ pc day^{-1}. In this case, the separation $\bar{r}$ of the Earth from the centre of the DP, formed by the signal laser radiation, is much smaller than the major semiaxis of the Earth orbit. For signals sent from other exoplanets considered in the present Section it is sufficient to aim the transmitting telescope at the Sun disk. The results of

Table 3. Parameters of telescopes for receiving signals from exoplanets to the Earth in the nonoptimal regime.

Exoplanet	D_0/m	D_t/D_0	$D_r\sqrt{ET_E T_e}$	D_r^{min}/m at $E = 2$ kJ	E/J at $D_r = 10$ m	$D_r\sqrt{ET_E T_e}/\bar{r}$	D_t/D_0	D_t/m
		$D_t = 10$ m		$T_e = T_E = 0.8$		$D_r = 10$ m, $E = 2$ J, $T_e = T_E = 0.8$		
Gliese 581 c	0.535	18.7	–	–	–	358	1.53	0.82
Gliese 163 c	1.29	7.75	–	–	–	358	1.53	2.0
Kepler-22 b	16.4	0.610	692	19	7500	358	1.53	25
Kepler-69 c	71.6	0.140	2880	80	130000	358	1.53	110
61 Virginis b	0.735	13.6	–	–	–	358	1.53	1.1
tau Ceti e	7.68	1.30	15.8	0.44	3.9	8730	0.0461	0.35

Table 4. Parameters of telescopes for receiving the signals from the Earth to exoplanets in the nonoptimal regime.

Exoplanet	D_0/m	D_t/D_0	$D_r\sqrt{ET_E T_e}$	D_r^{min}/m at $E = 2$ kJ	E/J at $D_r = 10$ m	$D_r\sqrt{ET_E T_e}/\bar{r}$	D_t/D_0	D_t/m
		$D_t = 10$ m		$T_e = T_E = 0.8$		$D_r = 10$ m, $E = 2$ J, $T_e = T_E = 0.8$		
Gliese 581 c	7.64	1.31	26.9	0.75	11	5110	0.0786	0.6
Gliese 163 c	10.4	0.965	58.7	1.6	54	2860	0.140	1.4
Kepler-22 b	19.3	0.518	683	19	7300	421	0.956	18
Kepler-69 c	112	0.0893	2880	80	130000	559	0.778	87
61 Virginis b	14.7	0.680	31.3	0.9	15	7150	0.0562	0.83
tau Ceti e	6.43	1.55	17.4	0.5	4.7	7300	0.0551	0.33

the calculations are presented in Table 3, which contains also the values of the ratio D_t/D_0 for $D_t = 10$ m and the values of the right-hand side of criterion (4), calculated for them. We would like to draw the attention to the fact that for sending the signals from the exoplanets Gliese 581 c, Gliese 163 c, and 61 Virginis b, located relatively close to the Sun, the ratio $D_t/D_0 > 3.83$, i.e., $D_t = 10$ m is too large for sending the signals to the Earth. The central spot of the DP appears to be so small compared to the uncertainty of the Earth position at the time of signal arrival that the Earth with the receiving device based on it can find itself far beyond the limits of the diffraction spot. For other planets $D_t/D_0 < 3.83$, which allowed the calculation of D_r^{min} of the Earth telescopes for the energy of the pulses sent from the exoplanets equal to 2 kJ, as well as, the required energy of the sent pulses received by the Earth-based telescopes with $D_r = 10$ m. In Table 4, the results of similar calculations are presented for the case when the laser signals are sent from the Earth to exoplanets.

From Tables 3, 4 one can see that with some of the presented exoplanets using the technical facilities, similar to those created at the Earth, it is possible to implement the communication, although not optimal, if these technical facilities and the orbit parameters satisfy the criterion, discussed in this paper. For example, sending a signal from the Earth towards Gliese 581 c, Gliese 163 c, 61 Virginis b in the optimal regime is impossible, but it can be implemented in the nonoptimal regime. However, sending a signal from these exoplanets towards the Earth is possible in the optimal regime.

For such an exoplanet as tau Ceti e using the existing facilities the signal can be sent in the optimal regime neither from the Earth, nor from the planet to the Earth. However, in the nonoptimal regime the two-side communication is possible. In this case, as seen from Tables 3, 4, the laser pulse energy required for establishing two-side communication does not exceed 5 J.

As to such exoplanets as Kepler-22 b and Kepler-69, it is still impossible to search for the signals, sent from these planets, as well as to send a signal that could be received at these exoplanets using the existing technical facilities. As seen from Tables 3, 4 this requires optical telescopes with essentially larger dimensions than the existing 10-metre telescopes, or the lasers with the energy of the emitted pulses essentially exceeding 3 kJ.

6. Conclusions

In the present paper, the interstellar laser communication between the Earth and exoplanets that enter the planetary systems of other stars is considered. We have found the implementability criterion of the interstellar laser communication in the case when, using the up-to-date large optical telescopes, the central spot of the diffraction pattern can be made comparable or even smaller than the orbit of the planet, and the signal arrives at the given segment of the orbit not synchronously with the planet because of the error in determining the distance between the Sun and the star around which the planet rotates.

Based on this criterion, we have determined the condition for optimising the communication that allows for the above non-synchronism by the estimation of the maximal distance from the diffraction pattern centre, at which the planet can unpredictably find itself at the time of the signal arrival. For the wavelength 1.315 μm, the optimal diameters of transmitting telescopes are calculated for sending the signals both to the Earth from the potentially inhabited exoplanets Kapetyn b, Gliese 667C c, Gliese 581 d, Gliese 581 c, Gliese 581 g, Gliese 163 c, Gliese 832 c, Kepler-22 b, Kepler-69 c, 61 Virginis b, HD 85512 b, and tau Ceti e (the range of distances from 3.6 to 830 pc) and to these planets from the Earth. It is clarified with which of the mentioned planets the optimal communication regime is possible using the telescopes with the diameter up to 10 m. It is shown that for 80% transmission of atmospheres of the planets the condition $D_r\sqrt{E}/\bar{r} > 432$ J$^{1/2}$ is to be satisfied. For the laser pulses with the energy 2 kJ we have calculated the diameters of the receiving telescopes installed both at the Earth and at the considered exoplanets. The requirements to the laser pulse energy are determined for the case of using the receiving telescopes with the diameter 10 m.

It is demonstrated that for the exoplanets Gliese 581 c, Gliese 163 c, Kepler-22 b, Kepler-69 c, 61 Virginis b, and tau

Ceti e the optimal communication regime is impossible using the telescopes with the diameter up to 10 m. We show, for which of them using such telescopes the communication is still possible, and for which planets larger telescopes or lasers with the pulse power exceeding 2 kJ will be necessary.

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