IAC-09.D4.1.4

REALISTIC TARGETS AT 1,000 AU FOR INTERSTELLAR PRECURSOR MISSIONS

Claudio Maccone

Co-Chair, SETI Permanent Study Group, International Academy of Astronautics
Address: Via Martorelli, 43 - Torino (Turin) 10155 - Italy
URL: http://www.maccone.com/ - E-mail: clmaccon@libero.it

ABSTRACT. The nearest stellar system, the Alpha Centauri three star system, is located about 4.40 light-years away. This amounts to 278,261 AU. But at only 550 AU, or, more generally, at only about 1,000 AU, the focus of the gravitational lens of the Sun is found, that is then 278 times closer than our nearest interstellar target. In other words, assuming equal engineering problems, the trip to the Sun focus takes 278 times less than the time to the nearest stellar target. This makes the Sun focus a reasonable target for our probes to reach within this century. It also plainly appears that, before we send a probe towards anyone of the nearest stellar systems, we will need a detailed radio map of that stellar system. In other words, we need a huge radio magnification of all objects located in that neighbourhood, and nothing is better than the huge magnification provided by the gravitational lens of the Sun. Thus, sending a preliminary probe to 1,000 AU in the direction opposite to the target stellar system clearly must be done before any interstellar flight to that stellar system is designed, not to say attempted. In this paper, a status review is presented about the "FOCAL" probe to 550 AU or 1000 AU. The relevant scientific, propulsion and telecommunication issues are briefly summarized and updated.

Keywords: Sun gravitational lens, space probe, special relativity, propulsion, telecommunications.

Reference: The recent book by the author: C. Maccone, Deep Space Flight and Communications, Praxis-Springer, 2009.

1. INTRODUCTION

The gravitational focusing effect of the Sun is one of the most amazing discoveries produced by the general theory of relativity. The first paper in this field was published by Albert Einstein in 1936 (ref. [1]), but his work was virtually forgotten until 1964, when Sydney Liebes of Stanford University (ref. [2]) gave the mathematical theory of gravitational focusing by a galaxy located between the Earth and a very distant cosmological object, such as a quasar.

In 1978 the first "twin quasar" image, caused by the gravitational field of an intermediate galaxy, was spotted by the British astronomer Dennis Walsh and his colleagues. Subsequent discoveries of several more examples of gravitational lenses eliminated all doubts about gravitational focusing predicted by general relativity.

Von Eshleman of Stanford University then went on to apply the theory to the case of the Sun in 1979 (ref. [3]). His paper for the first time suggested the possibility of sending a spacecraft to 550 AU from the Sun to exploit the enormous magnifications provided by the gravitational lens of the Sun, particularly at microwave frequencies, such as the hydrogen line at 1420 MHz (21 cm wavelength). This is the frequency that all SETI radioastronomers regard as "magic" for interstellar communications, and thus the tremendous potential of the gravitational lens of the Sun for getting in touch with alien civilizations became obvious.

The first experimental SETI radioastronomer in history, Frank Drake (*Project Ozma*, 1960), presented a paper on the advantages of using the gravitational lens of the Sun for SETI at the *Second International Bioastronomy Conference* held in Hungary in 1987 (ref. [4]), as did Nathan "Chip" Cohen of Boston University (ref. [5]). Non-technical descriptions of the topic were also given by them in their popular books (refs. [6] and [7]).

However, the possibility of planning and funding a space mission to 550 AU to exploit the gravitational lens of the Sun immediately proved a difficult task. Space scientists and engineers first turned their attention to this goal at the June 18, 1992, *Conference on Space Missions and Astrodynamics* organized in Turin, Italy, lead by me (see Figure 1.1). The relevant Proceedings were published in 1994 in the *Journal of the British Interplanetary Society* (ref. [8]). Meanwhile, on May 20, 1993 I also submitted a formal Proposal to the European Space Agency (ESA) to fund the space mission design (ref. [9]). The optimal direction of space to launch the FOCAL spacecraft was also discussed by Jean Heidmann of Paris Meudon Observatory and myself (ref. [10]), but it seemed clear that a demanding space mission like this one should not be devoted entirely to SETI. Things like the computation of the parallaxes of many distant stars in the Galaxy, the detection of gravitational waves by virtue of the very long baseline between the spacecraft and the Earth, plus a host of other experiments would complement the SETI utilization of this space mission to 550 AU and beyond.

The mission was dubbed "SETISAIL" in earlier papers (ref. [11]), and "FOCAL" in the proposal submitted to ESA in 1993.

In the third edition of his book "The Sun as a Gravitational Lens: Proposed Space Missions" (ref. 12), the author summarized all knowledge available as of 2002 about the FOCAL space mission to 550 AU and beyond to 1000 AU. On October 3rd, 1999, this book had already been awarded the Engineering Science Book Award by the International Academy of Astronautics (IAA).

Finally, in March 2009, the new, 400-pages and comprehensive book by the author, entitled "Deep Space Flight and Communications – Exploiting the Sun as a Gravitational Lens" (ref. [19]), was published. This book embodies all the previous material published about the FOCAL space mission and updates it.

2. WHY 550 AU IS THE MINIMAL DISTANCE THAT "FOCAL" MUST REACH

The geometry of the Sun gravitational lens is easily described: incoming electromagnetic waves (arriving, for instance, from the center of the Galaxy) pass *outside* the Sun and pass within a certain distance *r* of its center. Then the basic result following from the Schwarzschild solution shows that the corresponding *deflection angle α(r)* at the distance *r* from the Sun center is given by

$$\alpha(r) = \frac{4GM_{Sun}}{c^2 r}. \tag{1}$$

Figure 1 shows the basic geometry of the Sun gravitational lens with the various parameters in the game.

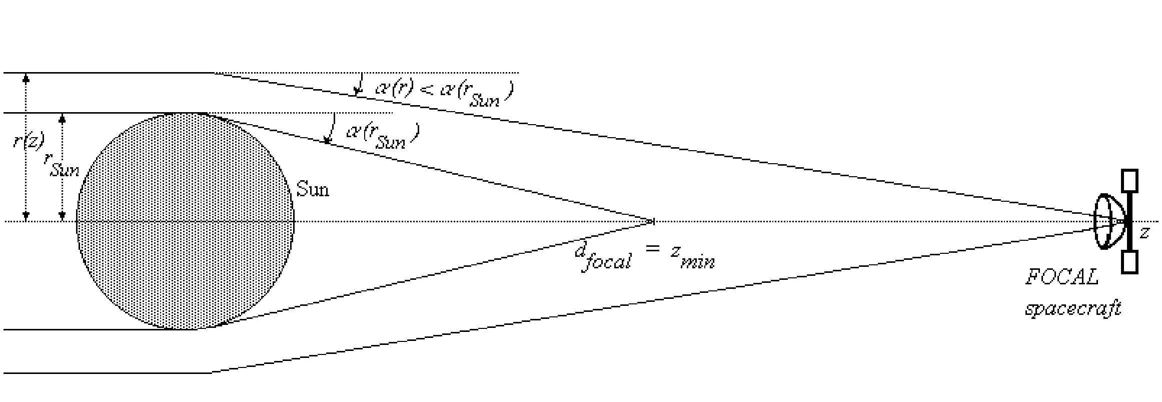


Figure 1. Geometry of the Sun gravitational lens with the minimal focal length of 550 AU (= 3.17 light days = 13.75 times beyond Pluto's orbit) and the FOCAL spacecraft position beyond the minimal focal length.

The light rays, i.e. electromagnetic waves, cannot pass through the Sun's interior (whereas gravitational waves and neutrinos can), so the largest deflection angle α occurs for those rays just grazing the Sun surface, i.e. for $r = r_{Sun}$. This yields the inequality

$$\alpha(r_{Sun}) > \alpha(r) \tag{2}$$

with

$$\alpha(r_{Sun}) = \frac{4GM_{Sun}}{c^2 r_{Sun}}. \tag{3}$$

From the illustration it should be clear that the minimal focal distance d_{focal} is related to the tangent of the maximum deflection angle by the formula

$$\tan(\alpha(r_{Sun})) = \frac{r_{Sun}}{d_{focal}}. \tag{4}$$

Moreover, since the angle $\alpha(r_{Sun})$ is very small (its actual value is about 1.75 arc seconds), the above expression may be rewritten by replacing the tangent by the small angle itself:

$$\alpha(r_{Sun}) \approx \frac{r_{Sun}}{d_{focal}}. \tag{5}$$

Eliminating the angle $\alpha(r_{Sun})$ between equations (3) and (5), and then solving for the minimal focal distance d_{focal}, one gets

$$d_{focal} \approx \frac{r_{Sun}}{\alpha(r_{Sun})} = \frac{r_{Sun}}{\frac{4GM_{Sun}}{c^2 r_{Sun}}} = \frac{c^2 r_{Sun}^2}{4GM_{Sun}} . \qquad (6)$$

This basic result may also be rewritten in terms the *Schwarzschild radius*

$$r_{Schwarzschild} = \frac{2GM_{Sun}}{c^2} , \qquad (7)$$

yielding

$$d_{focal} \approx \frac{r_{Sun}}{\alpha(r_{Sun})} = \frac{r_{Sun}}{\frac{4GM_{Sun}}{c^2 r_{Sun}}} = \frac{r_{Sun}^2}{2\, r_{Schwarzschild}} . \qquad (8)$$

Numerically, one finds

$$d_{focal} \cong 542 \text{ AU} \approx 550 \text{ AU} \approx 3.171 \text{ light days} . \qquad (9)$$

This is the fundamental formula yielding the minimal focal distance of the gravitational lens of the Sun, i.e. the minimal distance from the Sun's center that the FOCAL spacecraft must reach in order to get magnified radio pictures of whatever lies on the other side of the Sun with respect to the spacecraft position.

Furthermore, a simple, but very important consequence of the above discussion is that ***all points on the straight line beyond this minimal focal distance are foci too***, because the light rays passing by the Sun further than the minimum distance have smaller deflection angles and thus come together at an even greater distance from the Sun.

And the very important astronautical consequence of this fact for the FOCAL mission is that ***it is not necessary to stop the spacecraft at 550 AU. It can go on to almost any distance beyond and focus as well or better.*** In fact, the further it goes beyond 550 AU the less distorted the collected radio waves by the Sun Corona fluctuations. The important problem of Corona fluctuations and related distortions is currently being studied by Von Eshleman and colleagues at Stanford University (please refer to Chapter 6 of ref. [19].

We would like to add here one more result that is very important because it holds well not just for the Sun, but for all stars in general. This we will do without demonstration; that can be found on page 55 of ref. [12]. Consider a spherical star with radius r_{star} and mass M_{star}, that will be called the "focusing star". Suppose also that a light source (i.e. another star or an advanced extraterrestrial civilization) is located at the distance D_{source} from it. Then ask: how far is the minimal focal distance d_{focal} on the opposite side of the source with respect to the focussing star center? The answer is given by the formula

$$d_{focal} = \frac{r_{star}^2}{\frac{4GM_{star}}{c^2} - \frac{r_{star}^2}{D_{source}}} . \qquad (10)$$

This is the key to gravitational focussing for a pair of stars, and may well be the key to SETI in finding extraterrestrial civilizations. It could also be considered for the magnification of a certain source by any star that is perfectly aligned with that source and the Earth: the latter would then be in the same situation as the FOCAL spacecraft except, of course, it is located much further out than 550 AU with respect to the focussing, intermediate star. Finally, notice that equation (10) reduces to equation (6) in the limit $D_{source} \to \infty$, i.e. (6) is the special case of (10) for light rays approaching the focussing star from an infinite distance.

3. THE HUGE (ANTENNA) GAIN OF THE GRAVITATIONAL LENS OF THE SUN

Having thus determined the minimal distance of 550 AU that the FOCAL spacecraft must reach, one now wonders what's the good of going so far out of the solar system, i.e. how much focussing of light rays is caused by the gravitational field of the Sun. The answer to such a question is provided by the technical notion of "antenna gain", that stems out of antenna theory.

A standard formula in antenna theory relates the antenna gain, $G_{antenna}$, to the antenna effective area, $A_{effective}$, and to the wavelength λ or the frequency ν by virtue of the equation (refer, for instance, to ref. [13], in particular page **6**-117, equation (6-241)):

$$G_{antenna} = \frac{4\pi A_{effective}}{\lambda^2} . \qquad (11)$$

Now, assume the antenna is circular with radius $r_{antenna}$, and assume also a 50% efficiency. Then, the antenna effective area is obviously given by

$$A_{effective} = \frac{A_{physical}}{2} = \frac{\pi r_{antenna}^2}{2} . \qquad (12)$$

Substituting this back into (11) yields the antenna gain as a function of the antenna radius and of the observed frequency :

$$G_{antenna} = \frac{4\pi A_{effective}}{\lambda^2} = \frac{2\pi A_{physical}}{\lambda^2} =$$

$$= \frac{2\pi^2 r_{antenna}^2}{\lambda^2} = \frac{2\pi^2 r_{antenna}^2}{c^2} \cdot \nu^2 . \qquad (13)$$

The important point here is that *the antenna gain increases with the square of the frequency*, thus favoring observations on frequencies as high as possible.

Is anything similar happening for the Sun's gravitational lens also? *Yes* is the answer, and the "gain" (one maintains this terminology for convenience) of the gravitational lens of the Sun can be proved to be

$$G_{Sun} = 4\pi^2 \frac{r_{Schwarzschild}}{\lambda} \tag{14}$$

or, invoking the expression (1.2-7) of the Schwarzschild radius

$$G_{Sun} = \frac{8\pi^2\, G\, M_{Sun}}{c^2} \cdot \frac{1}{\lambda} = \frac{8\pi^2\, G\, M_{Sun}}{c^3} \cdot \nu\,. \tag{15}$$

The mathematical proof of equation (1.3-4) is difficult to achieve. The author, unsatisfied with the treatment of this key topic given in refs. [1], [3] and [13], turned to three engineers of the engineering school in his home town, Renato Orta, Patrizia Savi and Riccardo Tascone. To his surprise, in a few weeks they provided a full proof of not just the Sun gain formula (1.3-4), but also of the focal distance for rays originated from a source at finite distance, equation (1.2-10). Their proof is fully described in ref. [12], and is based on the aperture method used to study the propagation of electromagnetic waves, rather than on ray optics.

Using the words of these three authors' own Abstract, they have "computed the radiation pattern of the [spacecraft] Antenna+Sun system, which has an extremely high directivity. It has been observed that the focal region of the lens for an incoming plane wave is a half line parallel to the propagation direction starting at a point [550 AU] whose position is related to the blocking effect of the Sun disk (Figure 1). Moreover, a characteristic of this thin lens is that its gain, defined as the magnification factor of the antenna gain, is constant along this half line. In particular, for a wavelength of 21 cm, this lens gain reaches the value of 57.5 dB. Also a measure of the transversal extent of the focal region has been obtained. The performance of this radiation system has been determined by adopting a thin lens model which introduces a phase factor depending on the logarithm of the impact parameter of the incident rays. Then the antenna is considered to be in transmission mode and the radiated field is computed by asymptotic evaluation of the radiation integral in the Fresnel approximantion".

One is now able to compute the Total Gain of the Antenna+Sun system, that is simply obtained by multiplying equations the two equations yielding the spacecraft gain proportional to ν^3 and the Sun gain proportional to ν :

$$G_{Total} = G_{Sun} \cdot G_{antenna} = \frac{16\pi^4\, G\, M_{Sun}\; r_{antenna}^2}{c^5} \cdot \nu^3 \,. \tag{16}$$

Since the total gain increases with the *cube* of the observed frequency, it favors electromagnetic radiation in the microwave region of the spectrum. The table in Figure 2 shows the numerical data provided by the last equation for five selected frequencies: the hydrogen line at 1420 MHz and the four frequencies that the Quasat radio astronomy satellite planned to observe, had it been built jointly by ESA and NASA as planned before 1988, but Quasat was abandoned by 1990 due to lack of funding. The definition of dB is of course:

$$\mathrm{N\ dB} = 10\,\mathrm{Log}_{10}\mathrm{N} = \frac{10\,\ln\mathrm{N}}{\ln 10}\,. \tag{17}$$

Line	Neutral Hydrogen		OH radical		H_2O
Frequency ν	**1420 MHz**	**327 MHz**	**1.6 GHz**	**5 GHz**	**22 GHz**
Wavelength λ	21 cm	92 cm	18 cm	6 cm	1.35 cm
S/C Antenna Beamwidth	1.231 deg	5.348 deg	1.092 deg	0.350 deg	0.080 deg
Sun Gain	57.4 dB	51.0 dB	57.9 dB	62.9 dB	69.3 dB
12-meter Antenna S/C Gain	42.0 dB	29.3 dB	43.1 dB	53.0 dB	65.8 dB
Combined Sun + S/C Gain	**99.5 dB**	**80.3 dB**	**101.0 dB**	**115.9 dB**	**135.1 dB**

Table 1: Table showing the GAIN of the Sun's lens alone,the gain of a 12-meter spacecraft (S/C) antenna and the combined gain of the Sun+S/C Antenna system the at five selected frequencies important in radioastronomy.

4. THE IMAGE SIZE AT THE SPACECRAFT DISTANCE z

The next important notion to understand is the size of the image of an infinitely distant object created by the Sun lens at the current spacecraft distance z from the Sun ($z > 550\mathrm{AU}$). We may define such an image size as the distance from the focal axis (i.e. from the spacecraft straight trajectory) at which the gain is down 6 dB. The formula for this (proven in ref. [8]) is

$$r_{6dB} = \frac{\lambda}{\pi^2}\sqrt{\frac{z}{2r_s}} = \frac{c}{2\pi^2\sqrt{GM_{Sun}}}\lambda\sqrt{z} = \frac{c^2}{2\pi^2\sqrt{GM_{Sun}}}\frac{\sqrt{z}}{\nu}. \tag{18}$$

Thus the image size ***increases*** with the spacecraft distance z from the Sun. Table 2 shows how the image size increases with the spacecraft distance from the Sun in between the distances of 550 AU (minimal distance) and 1000 AU (maximal distance regarded as useful).

Line	Neutral Hydrogen		*OH* radical		H_2O
Frequency ν	1420 MHz	327 MHz	1.6 GHz	5 GHz	22 GHz
Wavelength λ	21 cm	92 cm	18 cm	6 cm	1.35 cm
Image size (down 6 dB) at 550 AU	2.498 km	10.847 km	2.217 km	0.709 km	0.161 km
Image size (down 6 dB) at 800 AU	3.033 km	13.169 km	2.691 km	0.861 km	0.196 km
Image Size (down 6 dB) at 1000 AU	3.391 km	14.724 km	3.009 km	0.963 km	0.219 km

Table 2: Table showing the IMAGE SIZES for a 12 meter FOCAL spacecraft antenna that has reached the distances of 550AU, 800 AU and 1000 AU from the Sun. for each of the five selected frequencies.

It is clear that these image size values are very small compared to the spacecraft distance from the Earth. This means that if we want to observe a certain point-source in the sky, the alignment between this source, the Sun and the spacecraft position must be extremely precise. In fact, the spacecraft tracking must exceed by far what we are able to do within the solar system today. However, this is not true if the source we want to observe is the center of the Galaxy, which is a very broad source: slight changes in the spacecraft trajectory (say in a spreading spiral shape) would enable us to gradually see much of the galactic center at the huge resolution provided by the gravitational lens of the Sun.

5. REQUIREMENTS ON THE IMAGE SIZE AND ANTENNA BEAMWIDTH AT THE SPACECRAFT DISTANCE z

There are two "geometrical" requirements that must be fulfilled in order that the combined lens system Sun+FOCAL spacecraft antenna can work at best:

1) **Size Requirement**: the full antenna dish of the FOCAL spacecraft must fall well inside the cylindrical region centered along the focal axis and having radius equal to r_{6dB}. That is, the spacecraft feed-dish radius must be considerably smaller than r_{6Db}, or, mathematically,

$$r_{Antenna} << r_{6dB} = \frac{c}{2\pi^2\sqrt{GM_{Sun}}}\lambda\sqrt{z} = \frac{c^2}{2\pi^2\sqrt{GM_{Sun}}}\frac{\sqrt{z}}{\nu}. \tag{19}$$

2) **Angle Requirement**: the impact-radius circle around the Sun within which electromagnetic waves are focussed towards the FOCAL spacecraft must fall well within antenna beamwidth of the FOCAL spacecraft. In a little more technical terms, the Half-Power Beam Width (=HPBW, i.e. the angular width of the main lobe of the spacecraft antenna at the half-power level) should be considerably greater than the angle subtended at the spacecraft distance by twice the incident ray impact radius at the Sun

$$HPBW >> 2\,\alpha(r) = \frac{8GM_{Sun}}{c^2\,r}. \tag{20}$$

Tables 3 and 4 show that both these conditions are fulfilled at the three FOCAL distances from the Sun and for our five selected frequencies.

Line	Neutral Hydrogen		OH radical		H_2O
Frequency ν	1420 MHz	327 MHz	1.6 GHz	5 GHz	22 GHz
Wavelength λ	21 cm	92 cm	18 cm	6 cm	1.35 cm
Image size at 550 AU vs. Antenna Radius	2.498 km >> 6 m	10.85 km >> 6 m	2.22 km >> 6 m	0.71 km >> 6 m	0.16 km >> 6 m
Image size at 800 AU vs. Antenna Radius	3.03 km >> 6 m	13.17 km >> 6 m	2.69 km >> 6 m	0.86 km >> 6	0.20 km >> 6 m
Image Size at 1000 AU vs. Antenna Radius	3.39 km >> 6 m	14.72 km >> 6 m	3.01 km >> 6 m	0.96 km >> 6 m	0.22 km >> 6 m

Table 3: Table showing the image sizes vs. the antenna radius for a 12 meter antenna located at various distances from the Sun for the five selected frequencies.

Line	Neutral Hydrogen		OH radical		H_2O
Frequency ν	1420 MHz	327 MHz	1.6 GHz	5 GHz	22 GHz
Wavelength λ	21 cm	92 cm	18 cm	6 cm	1.35 cm
HPBW at 550 AU vs. 2α	1.23154° >> 1.5×10^{-7} °	5.34798° >> 1.5×10^{-7} °	1.09299° >> 1.5×10^{-7} °	0.34976° >> 1.5×10^{-7} °	0.07949° >> 1.5×10^{-7} °
HPBW at 800 AU vs. 2α	1.23154° >> 1.5×10^{-7} °	5.34798° >> 1.5×10^{-7} °	1.09299° >> 1.5×10^{-7} °	0.34976° >> 1.5×10^{-7} °	0.07949° >> 1.5×10^{-7} °
HPBW at 1000 AU vs. 2α	1.23154° >> 1.5×10^{-7} °	5.34798° >> 1.5×10^{-7} °	1.109299° >> 1.5×10^{-7} °	0.34976° >> 1.5×10^{-7} °	0.07949° >> 1.5×10^{-7} °

Table 4: Table showing the Half-Power Beam Width (HPBW) vs. the aspect angle of the Sun for a 12 meter antenna located at various distances from the Sun for the five selected frequencies.

6. THE ANGULAR RESOLUTION AT THE SPACECRAFT DISTANCE *z*

The notion of angular resolution of the Sun lens is very relevant to the discussion that will follow in the second half of this paper, inasmuch as we will want to know which will be the linear resolution provided by a FOCAL spacecraft (with a 12-meter antenna) at three very different distances from the Sun:

1) The Galactic Center, distant about 30,000 AU or so from the Sun jointly with its huge, Galactic Black Hole (Sagittarius A*). Such a FOCAL space mission would be especially appealing to Astrophysicist and Cosmologists.
2) The Alpha Centauri system of three stars (Alpha Cen A, B and Proxima), located just 4.37 light-years away from the Sun. This FOCAL mission would be of special interest to the many, different scientists that regard the Alpha Centauri system as the first real target for the future Interstellar Flights.
3) Finally, we will provide an example of FOCAL space mission applied to one of the over 350 extrasolar planets that have been discovered since 1995. We selected the small one (above 1.9 Earth radius in radius) Gliese **Gliese 581 e** (or **Gl 581 e).** This is the fourth extrasolar planet found around Gliese 581, an M3V red dwarf star approximately 20.5 light-years away from Earth in the constellation of Libra. As described at the site http://en.wikipedia.org/wiki/Gliese_581_e, this planet was discovered by an Observatory of Geneva team lead by Michel Mayor, using the HARPS instrument on the European Southern

Observatory 3.6 m (140 in) telescope in La Silla, Chile. The discovery was announced on 21 April 2009. Mayor's team employed the radial velocity technique, in which the orbit size and mass of a planet are determined based on the small perturbations it induces in its parent star's orbit via gravity. At a minimum of 1.9 Earth masses, it is the smallest extrasolar planet discovered around a normal star, and the closest in mass to Earth. At an orbital distance of just 0.03 AU from its parent star, however, it is outside the habitable zone. It is unlikely to possess an atmosphere due to its high temperature and strong radiation from the star. Although scientists think it probably has a rocky surface similar to Earth, it is also likely to experience intense tidal heating similar to (and likely more intense than) that affecting Jupiter's moon Io. Gliese 581e completes an orbit of its sun in approximately 3.15 days.

Having so described three different targets for three different FOCAL space missions, we complete this section by pointing out that the Angular Resolution provided by FOCAL simply is defined as the ratio of the image size (at the spacecraft distance z from the Sun) to that distance z. From (18), we thus get:

$$\theta_{resolution}(z) = \frac{r_{6dB}}{z} = \frac{c^2}{2\pi^2\sqrt{GM_{Sun}}} \cdot \frac{1}{\sqrt{z}\,\nu} . \qquad (21)$$

Clearly ***the angular resolution*** also depends on the spacecraft distance z from the Sun, and it actually ***improves (i.e. it gets smaller)*** as long as the distance increases beyond 550 AU. This is an advantage, of course, and one more reason (apart from avoiding the Corona effects) to let FOCAL reach distances above 550 AU and up to 1000 AU.

Line	Neutral Hydrogen		OH radical		H_2O
Frequency ν	1420 MHz	327 MHz	1.6 GHz	5 GHz	22 GHz
Wavelength λ	21 cm	92 cm	18 cm	6 cm	1.35 cm
Angular Resolution at 550 AU S/C distance	6.3458 x 10^{-6} arcsec	2.7557 x 10^{-5} arcsec	5.6319 x 10^{-6} arcsec	1.8022 x 10^{-6} arcsec	4.0959 x 10^{-7} arcsec
Angular Resolution at 800 AU S/C distance	5.2267 x 10^{-6} arcsec	2.2697 x 10^{-5} arcsec	4.6387 x 10^{-6} arcsec	1.4844 x 10^{-6} arcsec	3.3736 x 10^{-7} arcsec
Angular Resolution at 1000 AU S/C distance	4.6749 x 10^{-6} arcsec	2.0301 x 10^{-5} arcsec	4.1490 x 10^{-6} arcsec	1.3277 x 10^{-6} arcsec	3.0174 x 10^{-7} arcsec

Table 5: Angular resolution at spacecraft distances of 550 AU, 800 AU and 1000 AU, at the five selected frequencies.

Table 5 gives the angular resolutions for the same three FOCAL spacecraft distances of 550 AU, 800 AU and 1000 AU from the Sun, at the same five selected frequencies. Let us take a moment to ponder over these numbers. The best angular resolutions achieved so far, in visible light, were obtained by the European astrometric satellite *Hipparcos*, launched in 1989, and dismissed from service in 1993. Though the apogee kick motor of Hipparcos didn't fire, forcing technicians to take the software originally written for a circular geostationary orbit and re-write it for a highly elliptical orbit, the Hipparcos mission has proven a success. The resolutions achieved by Hipparcos are at a level of 2 milliseconds of arc precision. Checking this figure against the above table, one can see that the gravitational lens of the Sun plus a (modest) 12-meters antenna would improve the angular resolution by about ***three orders of magnitude*** (at radio frequencies).

7. THE SPATIAL RESOLUTION AT THE SPACECRAFT DISTANCE *z*

Finally, let us turn to the ***spatial resolution***, simply called the ***resolution*** hereafter, of an astronomical object we want examine by help of the gravitational lens of the Sun. It defined by

$$R_{Object} = d_{Sun-Object}\theta_{resolution} = d_{Sun-Object}\frac{c^2}{2\pi^2\sqrt{GM_{Sun}}}\frac{1}{\sqrt{z\nu}} . \qquad (22)$$

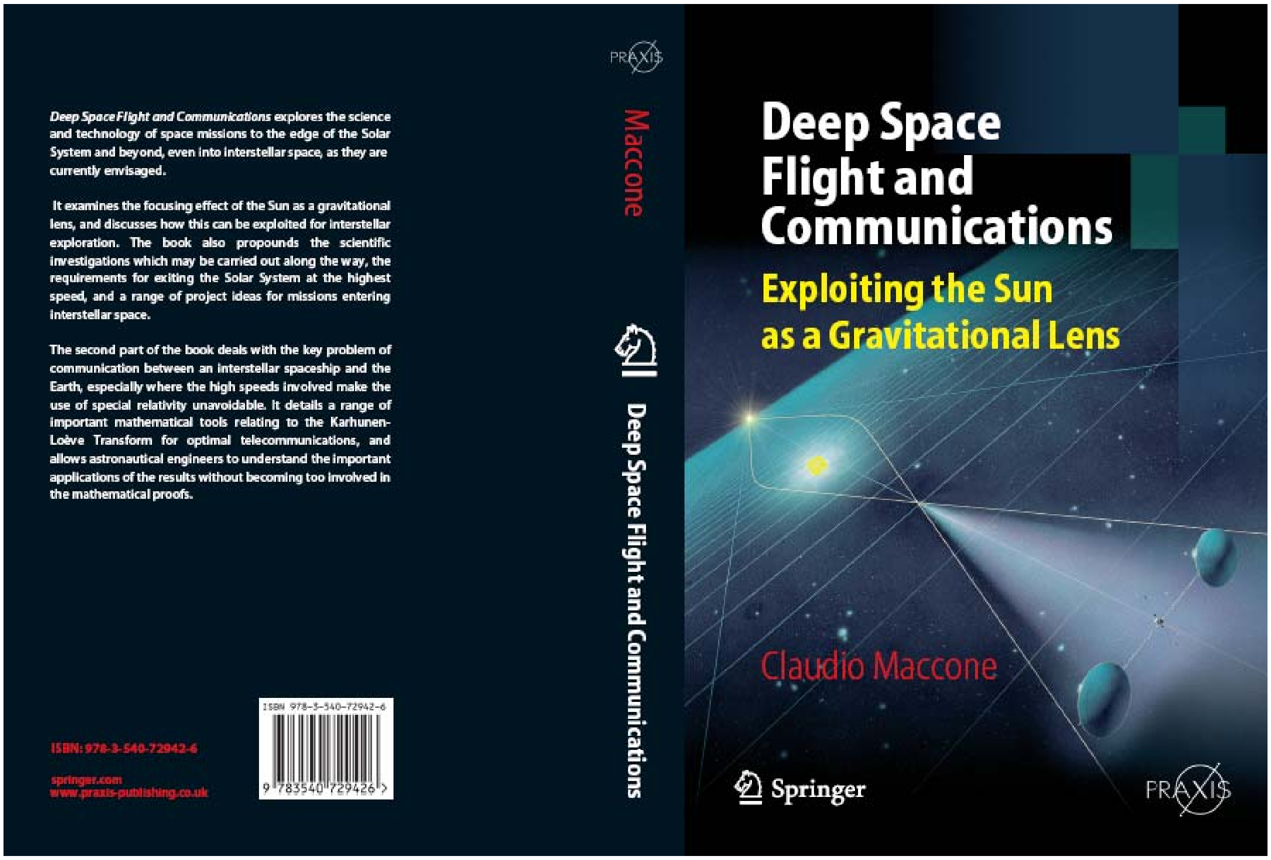
Again, beyond 550 AU the resolution improves (i.e. the angle gets smaller) slowly with the increasing spacecraft distance from the Sun. The following Table 6 shows the spatial resolutions for a very wide range of distances, from the Oort Cloud to cosmological objects like quasars.

Line	Neutral Hydrogen		OH radical		H_2O
Frequency ν	1420 MHz	327 MHz	1.6 GHz	5 GHz	22 GHz
Wavelength λ	21 cm	92 cm	18 cm	6 cm	1.35 cm
Resolution at 0.5 ly Oort Cloud	145 km	632 km	129 km	41 km	9 km
Resolution at 4.29 ly α Centauri	1,248 km	5,422 km	1,108 km	355 km	81 km
Resolution at 10 pc = 32.6 ly	9,576 km	41,58 km	8,499 km	2,719 km	618 km
Resolution at 100 pc = 326 ly	95,75 km	415,8 km	84,98 km	27,19 km	6,180 km
Resolution at 1 kpc = 3,260 ly	957,58 km = 0.006 AU	4,158,330 km = 0.028 AU	849,861 km = 0.005 AU	271,955 km = 0.001AU	61,808 km = 0.0004AU
Resolution at 10 kpc = 32,600 ly GALACTIC CENTER	9,575,870 km = 0.06401 AU	41,583,000 km = 0.27797 AU	8,498,610 km = 0.05681 AU	2,719,550 km = 0.01818 AU	618,082 km = 0.00413 AU
Resolution at 50 kpc = 160,000 ly Magellanic Clouds	4.78794 x 10^{7} km = 0.32006 AU	2.07917 x 10^{8} km = 1.38984 AU	4.2493 x 10^{7} km = 0.28405 AU	1.3597 x 10^{7} km = 0.0909 AU	3.0903 x 10^{6} km = 0.02066 AU
Resolution at 613 kpc = 2 million ly Andromeda Galaxy M31	5.82123 x 10^{8} km = 3.89125 AU	2.52788 x 10^{9} km = 16.8978 AU	5.16631 x 10^{8} km = 3.45349 AU	1.65322 x 10^{8} km = 1.10512 AU	3.75732 x 10^{7} km = 0.25116 AU
Resolution at 18,406 pc = 60 million ly "Jet" Galaxy M87 inVirgo	1.74636 x 10^{10} km = 116.738 AU	7.5836 x 10^{10} km = 506.934 AU	1.5499 x 10^{10} km = 103.605 AU	4.95968 x 10^{10} km = 33.1535 AU	1.1272 x 10^{9} km = 7.53488 AU
Resolution at 3.07 million kpc = 10 billion ly Radius of the Universe	2.91059 x 10^{12} km = 19,456 AU = 0.30765 ly	1.26393 x 10^{13} km = 84,489 AU = 1.33598 ly	2.58316 x 10^{12} km = 17,267 AU = 0.27304 ly	8.2661 x 10^{11} km = 5525.58 AU = 0.08737 ly	1.8786 x 10^{11} km = 1255.81 AU = 0.01986 ly

Table 6: Spatial resolutions for astronomical objects at selected distances from the Sun (12-meter spacecraft antenna). This shows the advantages of FOCAL for the whole of Astronomy: Planetary, Galactic and Cosmological.

8. THE 2009 NEW BOOK BY THE AUTHOR ABOUT THE “FOCAL” SPACE MISSION

In March 2009, the new, 400-pages and comprehensive book by the author, entitled “Deep Space Flight and Communications – Exploiting the Sun as a Gravitational Lens” (ref. 19), was published. This book embodies all the previous material published about the FOCAL space mission and updated it in view of submitting a formal Proposal to NASA about FOCAL. The front and back covers of this book are reproduced in Figure 3 below.



Deep Space Flight and Communications explores the science and technology of space missions to the edge of the Solar System and beyond, even into interstellar space, as they are currently envisaged.

It examines the focusing effect of the Sun as a gravitational lens, and discusses how this can be exploited for interstellar exploration. The book also propounds the scientific investigations which may be carried out along the way, the requirements for exiting the Solar System at the highest speed, and a range of project ideas for missions entering interstellar space.

The second part of the book deals with the key problem of communication between an interstellar spaceship and the Earth, especially where the high speeds involved make the use of special relativity unavoidable. It details a range of important mathematical tools relating to the Karhunen-Loève Transform for optimal telecommunications, and allows astronautical engineers to understand the important applications of the results without becoming too involved in the mathematical proofs.

ISBN: 978-3-540-72942-6

springer.com
www.praxis-publishing.co.uk

ISBN 978-3-540-72942-6

Maccone

Deep Space Flight and Communications

Deep Space
Flight and
Communications

Exploiting the Sun
as a Gravitational Lens

Claudio Maccone

Springer

PRAXIS

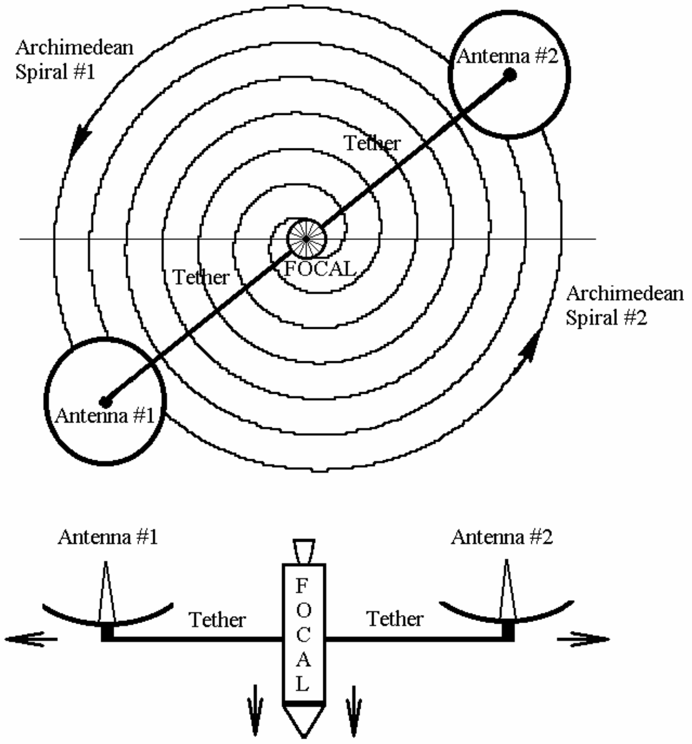
Figure 3. Front and back covers of the author’s new book entitled “Deep Space Flight and Communications – Exploiting the Sun as a Gravitational Lens” published by Springer-Praxis in March 2009, see ref. [19].

9. USING TWO ANTENNAE AND A TETHER TO GET A MUCH LARGER FIELD OF VIEW FOR FOCAL

The goal of this section is to put forward the new notion of a TETHERED SYSTEM tying up TWO ANTENNAE for the FOCAL spacecraft. We are going to show that the length of this tether system does not need to be very long: actually, just a couple of km or so is sufficient to get a radio picture of the big Galactic Black Hole, and this is a good result because a 2 km tether is certainly technologically feasible. It is important to point out that the tether could possibly be replaced by a *truss*. This would of course increase the system stability. To build a 2-km long truss in space, however, is a difficult engineering task. We thus prefer to speak about a tethered system rather than a truss system, leaving the actual design to expert engineers.

We start by pointing out the problem of the Sun corona plasma fluctuations with the relevant disturbances caused upon the radio waves passing through the corona itself, as described in Chapters 8 and 9 of the author’s 2009 book (ref. [19]). Finding a solution to this problem is vital for the success of the FOCAL space mission. We now claim that the best way to solve the corona problem is by doing ***interferometry*** between *two* antennas of the FOCAL spacecraft. Thus, the FOCAL spacecraft, rather than having just one antenna (inflatable and, say, 12 meters in diameter), must have ***two identical antennas*** in the new configuration proposed here. This doubles the sensitivity of the system, and, additionally, introduces the new and fruitful idea of a tether ting up each of them to the main cylindrical body of the FOCAL spacecraft, as shown in Figure 4.

Figure 4. Enlarged part of the front cover of the author's 2009 book (ref. [19]) showing: 1) The bright radio source at infinity (i.e. the horizon); 2) its radio waves flying by the Sun and made to focus at 550 AU; 3) the FOCAL spacecraft made up by two (say) 12-meter antennae tied to each other by a THETHER and revolving in the orthogonal plane to the spacecraft's velocity vector. The same is shown here below, with the two Archimedean Spirals covered by the antennae.



Thus, the tethered FOCAL system we wish to propose is described as follows:

1) The whole spacecraft moves away from the Sun along a rectilinear, purely radial trajectory.
2) When the distance from the Sun is, say, 400 to 500 AU, all "engines" (solar sails? nuclear-electric? antimatter?) are turned off, so we can assume that, at least beyond 550 AU, the Sun-speed of the whole system is ***uniform.***
3) Uniform speed means no acceleration. So, one can start deploying the tether. The body of the FOCAL spacecraft is supposed to be cylindrical and kept in rotation at a suitable angular speed (i.e. FOCAL is supposed to be spin-stabilized). On two opposite sides of the cylinder, the two packed, inflatable antennas are put out of the spacecraft. And each antenna is tied to the spacecraft by a tether kept tense because of the angular rotation of the whole system.
4) The two antennas are inflated at the same time just after they have reached the minimal safety distance from the spacecraft.
5) The two antennas are oriented and pointed each toward the Sun. This means that the two antenna axes are parallel or nearly-parallel to each other. The, in practice, a huge isosceles triangle is created in space, having as basis the distance between the two antennas and as apex the center of the Sun (at any distance higher than 550 AU).
6) Slowly, both tethers are deployed by the same amount of length on each side of FOCAL. Because of the uniform angular rotation of the whole system, this means that the end-points of the tether, i.e. the center of each antenna, is made to describe an Archimedean spiral (i.e. a spiral with polar equation $\rho(\theta) = const \cdot \theta$) around the axis of the FOCAL cylindrical spacecraft. And, in turn, this fact actually means much more: since each antenna is pointing to the Sun, then… On the other side of the Sun, at the distance of the galactic center (i.e. about 32,000 light years away) two "huge" Archimedean spirals are correspondingly being described around the galactic center. Just at the center, a "huge" black hole is suspected to exist, as depicted in Figure 5 hereafter. This gigantic black hole we call the Galactic Black Hole, as described in the next section.

10. OBSERVING THE GALACTIC BLACK HOLE MAGNIFIED BY VIRTUE OF FOCAL

7) On the other side of the Sun, at the distance of the Galactic Bulge (i.e. some 26,000 to 32,000 light years away) two "huge" Archimedean spirals are correspondingly being described around the Galactic Center. Just at the center, a "huge" black hole is suspected to exist, as depicted in Figure 5 hereafter. This gigantic black hole we call the Galactic Black Hole, and provisionally assign to it the estimated mass of a million times the mass of the Sun (as of 2009, its estimated mass is actually 4.31 ± 0.06 Sun masses). Consequently, the Schwarzschild radius of the galactic black hole is a million times larger than the Sun Schwarzschild radius, i.e. it equals ~ $2.95\text{x}10^9$ km ~ 0.01976 AU. This linearity between mass and Schwarzschild radius obviously appears in the definition (7).

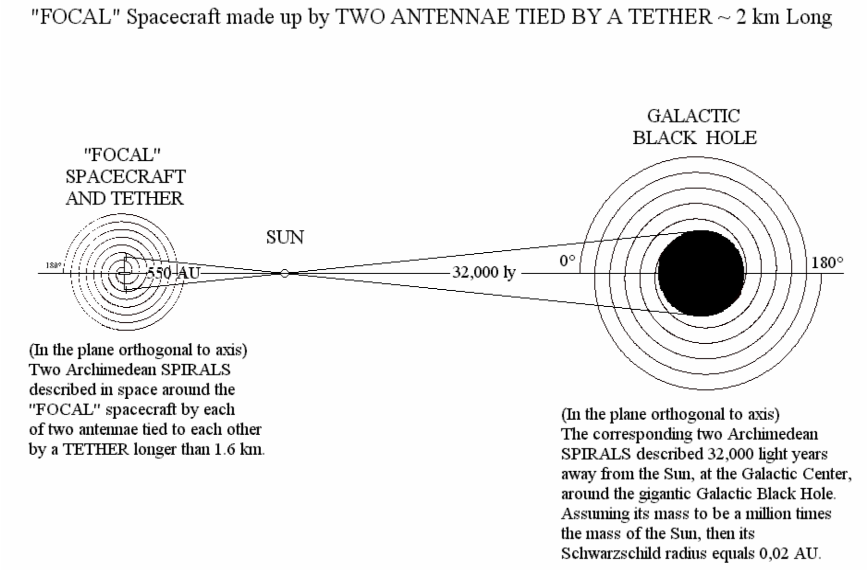


Figure 5. Imagine the above two Archimedean spirals in parallel planes both ORTHOGONAL to the axis FOCAL, Sun Center, Galactic Center. Then, two SIMILAR TRIANGLES relate the FOCAL tether length, the FOCAL spacecraft distance from the Sun, the size of the Galactic Black Hole and its distance from the Sun. They allow us to compute the MINIMAL THETHER LENGTH.

8) We are now able to estimate the minimal tether length necessary to include the whole of the Galactic Black Hole within the area encompassed by the two FOCAL Archimedean spirals. Figure 5 clearly shows the two "similar" isosceles triangles: i) the "small" one, between the tethered FOCAL system and the Sun, and ii) the "large" one, between the Sun and the galactic black hole. These two similar triangles yield immediately the proportion:

$$\frac{Minimal\ Tether\ Length}{550\ AU} = \frac{2\ r_{Schwarzschild\ of\ Galactic\ Black\ Hole}}{32{,}000\ light\ years} \tag{23}$$

But the Galactic Black Hole Schwarzschild radius is simply given by the Schwarzschild radius formula (7)

$$r_{Schwarzschild\_of\_Galactic\_Black\_Hole} = \frac{2GM_{Galactic\_Black\_Hole}}{c^2}. \tag{24}$$

Astronomers have recently estimated the mass of the Galactic Black Hole to equal some four million solar masses. This is described at the Wikipedia site http://en.wikipedia.org/wiki/Sagittarius_A* . There one finds that, monitoring stellar orbits around Sagittarius A* for 16 years, the following conclusion was announced in 2008 by Reinhard Genzel, team leader of the research study: "The stellar orbits in the galactic centre show that the central mass concentration of four million solar masses must be a black hole, beyond any reasonable doubt." Thus, replacing (23) into (22) and s

$$Minimum\ Tether\ Length = 1.6\ km. \tag{25}$$

for the basic case of 1 million solar masses for Galactic Black Hole. If the real value is four times as much, we must multiply (20) by four, getting 6.4 km. Also, the distance of the galactic center was changed by astronomers in recent years, letting it get down from 32,000 light years to about 26,000 light years. And, since the actual tether length must be higher than this minimal tether length, ***we reach the conclusion that a tether about 10 km long would certainly allow us to see not just the Galactic Black Hole, but also a host or astrophysical phenomena taking place around it, like the "swallowing" of stars by the Galactic Black Hole. In fact, from Table 6, row 9, we see that the linear resolution provided by FOCAL at the Galactic Center ranges between 1/10 and 1/100 AU.***

To sum up, it is believed that the 21st and following centuries are likely to see a host of FOCAL space missions, each one devoted to a different stellar target and thus launched along a different direction out of the solar system. And the guess is made here that all of them will use the tethered system as described in this section to avoid, by virtue of interferometry, all the problems caused by random fluctuations occurring within the Sun's corona.

11. OBSERVING THE 3 ALPHA CENTAURI STARS MAGNIFIED BY VIRTUE OF FOCAL

Alpha Centauri (α Centauri / α Cen) is a triple star system and is the brightest star system in the southern constellation of Centaurus. Alpha Centauri AB (α Cen AB) is a close binary system revolving in 79.91 years. To the unaided eye it appears as a single star, whose total visual magnitude would identify it as the third brightest star in the night sky. As we all know, the triple Alpha Centauri system is the ***closest star system*** to the Solar System, the center of gravity of α AB Cen being only 1.34 parsecs, or 4.37 light years away from our Sun. Because of this, the very first truly interstellar space mission will very likely be aimed at reaching the Alpha Centauri system, rather than any other nearby star system in the Galaxy.

From site http://en.wikipedia.org/Alpha_centauri (the Alpha Centauri Wikipedia site), we learn that the star called Alpha Centauri A is the principal member or ***primary*** of the binary system, being slightly larger and more luminous than our Sun. It is a solar-like main sequence star with a similar yellowish-white color, whose stellar classification is spectral type G2 V. From the determined mutual orbital parameters, α Cen A is about 10% more massive than our Sun, with a radius about 23% larger. The projected rotational velocity ($v \cdot \sin i$) of this star is 2.7±0.7 km·s^{-1}, resulting in an estimated rotational period of 22 days, which gives it a slightly faster rotational period than our Sun's 25 days.

The star Alpha Centauri B is the companion star or ***secondary***, slightly smaller and less luminous than our Sun. This main sequence star is of spectral type of K1 V, making it more an orangish-yellow color than the whiter primary star. α Cen B is about 90% the mass of the Sun and 14% smaller in radius The projected rotational velocity ($v \cdot \sin i$) is 1.1±0.8 km·s^{-1}, resulting in an estimated rotational period of 41 days (An earlier estimate gave a similar rotation period of 36.8 days). Although it has a lower luminosity than component A, star B's spectrum emits higher energies in X-rays. The light curve of B varies on a short time scale and there has been at least one observed flare.

Finally, Alpha Centauri C, also known as Proxima Centauri, is of spectral class M5Ve or M5VIe, suggesting that this is either a small main sequence star (Type V) or sub-dwarf (VI) with emission lines, whose B-V color index is +1.81. Its mass is about 0.12 times the Sun mass. Proxima is approximately 12,000 or 13,000 AU away from Alpha Cen AB and its orbital period around them is of the order of 100,000 to 500,000 years or more (its orbit might even be hyperbolic). Because of this situation, Proxima is indeed the closest star to us at all, its distance being 4.243 ± 0.002 ly (1.3009 ± 0.0005 pc).

We now want to clarify the notion of ***Position angle***, usually abbreviated ***PA*** and defined as the angular offset in degrees of the secondary star to the primary, relative to the north celestial pole. This is visually described in the following Figure 6, taken from the relevant Wikipedia site,

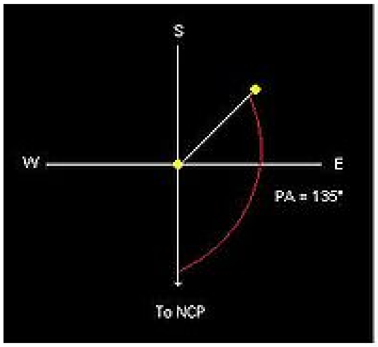


Figure 6. How the position angle PA is estimated through a telescope eyepiece. The primary star is at center. If one were observing a hypothetical binary star with a PA of 135 degrees, that means an imaginary line in the eyepiece drawn from the north celestial pole (NCP) to the primary (P) would be offset from the secondary (S) such that the NCP-P-S angle would be 135 degrees. The NCP line is traditionally drawn downward--that is, with north at bottom--and PA is measured counterclockwise, from 0 to 359 degrees (from site http://en.wikipedia.org/wiki/Position_angle).

Let us now go back to the Alpha Centauri system.

Viewed from Earth, the ***apparent orbit*** of this binary star system means that the separation and position angle are in continuous change throughout the projected orbit. Observed stellar positions in 2008 are separated by 8.29 arcsec through a P.A. of 237°, reducing to 7.53 arcsec through 241° in 2009. Next closest approach will be in February 2016, at 4.0 arcsec through 300°. Observed maximum separation of these stars is about 22 arcsec, while the minimum distance is a little less than 2 arcsec. Widest separation occurred during February 1976 and the next will be in January 2056 (see Figure 7 for B's apparent trajectory with respect to A).

In the ***true orbit,*** closest approach or periastron was in August 1955; and next in May 2035. Furthest orbital separation at apastron last occurred in May 1995 and the next will be in 2075. Thus, the apparent distance between the two stars is presently decreasing.

Going now back to the FOCAL space mission, the first question we wish to answer is: can we use a tethered system of two antennae to watch the Alpha Centauri system (as it is possible to do in order to observe the Galactic Black Hole? Unfortunately, the answer is "no", since the tether length would be far too long: of the order of millions of km !

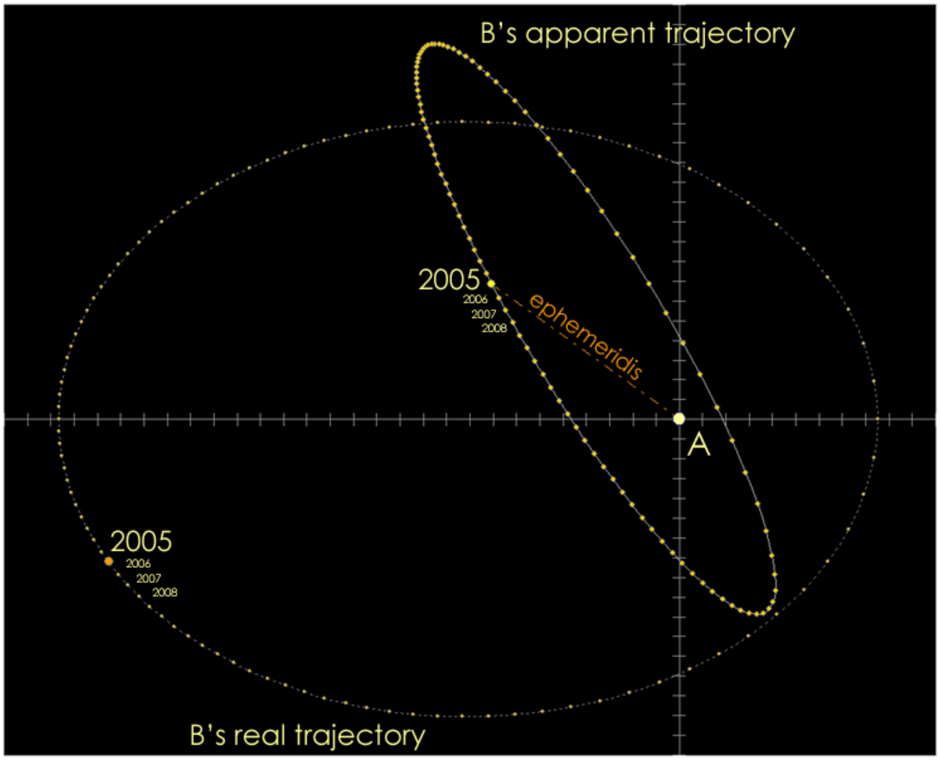


Figure 7. Apparent and True Orbits of Alpha Centauri B (the secondary) around Alpha Centauri A (the primary).. Motion is shown from the A component against the relative orbital motion of B component. The Apparent Orbit (thin ellipse) is the shape of the orbit as seen by the observer on Earth. The True Orbit is the shape of the orbit viewed perpendicular to the plane of the orbital motion (taken from site http://en.wikipedia.org/wiki/Alpha_Centauri).

To realize why it is so, just compute the expression

$$550 * \mathrm{AU} * \tan\left(\frac{22 * \mathrm{arcsec}}{2}\right) = 4.388 * 10^6\,\mathrm{km} \qquad (26)$$

yielding the tether length requested to encompass the view of both A and B at their maximum visual separation of 22 arcsec. Even if we consider the minimal visual separation of 4 arcsec, this is no better:

$$550 * \mathrm{AU} * \tan\left(\frac{4 * \mathrm{arcsec}}{2}\right) = 7.978 * 10^5\,\mathrm{km} \qquad (27)$$

So, a tethered system to encompass the whole A-B system is out of consideration. But this does not mean that a tethered system can be adopted to visualize ***each*** of the two stars separately: simply, it would provide too a narrow field of view because the whole system it just too close to the Sun.

So, we must resort to some other idea.

The new idea proposed here for the first time is to change the FOCAL orbit beyond 550 AU from a just an outgoing straight line to a CONICAL HELIX OF INCREASING RADIUS.

To understand immediately what this means, consider… the famous building of the Guggenheim Museum in New York City, shown in Figure 8 below as if it was tilted from right to left..

Figure 8. The building of the Guggenheim Museum in New York City… shown tilted by 90 degrees, as if it was lying horizontally on the ground rather than vertically! Then, from right to left in this picture, the profile of this building is a CONICAL HELIX of increasing radius.

The profile of this building is a conical helix, and if you look at it from right to left, you have just the conical helix, i.e. the helix in on the surface of a cone with apex at just 550 AU and then higher and higher radius. ***This is the modified orbit we propose for FOCAL after 550 AU.***

But how to achieve such an orbit in space?

Well, we need a small but continue thrust, like those used in electric propulsion and called FEEP, an acronym for Field Emission Electric Propulsion: see, the relevant Wikipedia site and references therein: http://en.wikipedia.org/wiki/Field_Emission_Electric_Propulsion

Actually, the acceleration produced by these FEEPs is so small, and the times involved in having the FOCAL spacecraft moving along its conical helix trajectory are so large (decades), that one might well add a tethered system revolving orthogonal to the speed vector, as described for the observation pf the Galactic Black Hole. The radio image of the Alpha Cen system would then appear more and more detailed over the years while FOCAL would travel from 550 to 1000 AU along its conical helix trajectory.

We stop our description at this point, for the next step would require an accurate engineering design and an excellent astrodynamical calculation of the conical helix, both of which we do not have the time to compute now. But the idea of the conical helix plus a thether is a good one, and will have to be developed in further papers by this or other authors.

12. OBSERVING EXTRASOLAR PLANETS MAGNIFIED BY VIRTUE OF FOCAL

The most important discovery in Astronomy after 1995 is probably the discovery of extrasolar planets. As of August 2009, 373 exoplanets are listed in the Extrasolar Planets Encyclopaedia. We thus wish to conclude this paper by providing an example of how the FOCAL space mission would be able to provide largely magnified images of extrasolar planets.

For instance, consider **Gliese 581 e** (or **Gl 581 e),** the fourth extrasolar planet found around Gliese 581, an M3V red dwarf star approximately 20.5 light-years away from Earth in the constellation of Libra. The planet was discovered by an Observatory of Geneva team lead by Michel Mayor, using the HARPS instrument on the European Southern Observatory 3.6 m (140 in) telescope in La Silla, Chile. The discovery was announced on 21 April 2009.

Going now back to FOCAL, consider (22) again:

$$R_{Object} = d_{Sun\text{–}Object}\,\theta_{resolution} = d_{Sun\text{–}Object}\,\frac{c^2}{2\pi^2\sqrt{GM_{Sun}}}\,\frac{1}{\sqrt{z\nu}}. \qquad (22)$$

This is the linear resolution of our extrasolar planet radio-pictures provided by FOCAL. In (22) we know:

1) The distance between the Sun and the target star, $d_{Sun\text{-}Object}$ given by the Hipparcos Catalogue;
2) The distance z between the Sun and the FOCAL spacecraft after it reached at least 550 AU away from the Sun;
3) The observing frequency ν that we can choose at will (with many technological constraints) when we design the FOCAL spacecraft dedicated to observe that particular extrasolar planet only.

So, the key variable is the frequency, of course, and (22) neatly shows that the higher the frequency, the smaller (i.e. the better) is the linear resolution provided by FOCAL.

We just wanted to point this clearly out

The interested reader may wish to read more by consulting the author's recent book [19], especially Chapter 9 and Section 9.4, where the Sun's Coronal Effects are taken into account also.

Thanks very much.

CONCLUSION

In these few pages we could just sketch the FOCAL space mission to 550 AU and beyond to 1000 AU.
A number of issues still have to be investigated in:

1) the many scientific aspects related to the mission,
2) in the propulsion tradeoffs to get there in the least possible time and
3) the optimization of the telecommunication link.

Yet, it plainly appears that the Sun focus at 550 AU is the next most important milestone that Humankind must reach in order to be prepared for the following and more difficult task of achieving the interstellar flight.

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