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# An Evaluation of the Communication System for the TAU Mission Study

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*The requirements for possible microwave and optical frequency communication systems to return 20 kbps from 1000 AU are compared and sample telemetry links are calculated. Microwave systems were found to have impractical parameter requirements, while the required optical system parameters are much more feasible. A first-level design of an optical communication link is presented; this design can be implemented with conservatively projected technology development. Optical background noise can be either tolerated or eliminated and it was found that TAU could detect a laser beacon from Earth even if Earth were in front of the sun.*

## I. Introduction

TAU is a proposed mission currently under study at JPL to send a probe to a distance of one thousand astonomical units (AU). Among the possible science objectives for this mission are high-precision astrometry using a 1000-AU baseline, low-frequency radio astronomy, measurements of the interstellar medium, and imaging of our solar system from the outside. These and other science experiments on TAU will require a communication system capable of returning data to Earth from 1000 AU at rates of up to 20 kilobits per second (kbps). In this study, possible radio-frequency (Ka-band, 32 GHz) and optical-frequency (532 nm) communications systems were examined and their requirements and capabilities assessed.

The radio-frequency technology currently used for deep space communications has several advantages over the less mature optical technology. A microwave communication system for TAU would require less developmental work. A microwave transmission beam need not be pointed as accurately as a more tightly focused optical beam and power conversion efficiencies are generally higher for radio transmitters than for lasers. Microwave communication links can use ground based receiving antennas, whereas optical frequencies are attenuated far more by the atmosphere and will probably require space-based receiving telescopes for deep-space links.

However, in order to return the 20 kbps required for TAU mission science from a 1000 AU, a microwave system would require transmitting and receiving antennas that are too large to be practical, as well as more power than would be required by an optical system. Given a sufficient power supply, TAU would still require a microwave transmitting antenna at least 10 to 15 meters in diameter and a receiving antenna 200 meters in diameter (or an equivalent receiver array).

Advantages of using an optical communication system for the TAU mission include much lower diffraction limited beam divergence, much smaller and lighter transmitting and receiving antennas, and the ability to support high data rates.

Design control tables for these two options are presented and the requirements and performance of each is discussed. The design of an optical communications link for TAU is considered further, with an assessment of noise sources, a design table for the uplink, and a brief look at acquisition and tracking.

## II. Comparison of Microwave and Optical Communications Links

### A. Requirements for a Radio Frequency Link

A Ka-band communications link for TAU would need a transmitter antenna 10 to 15 meters in diameter. Antennas larger than 4.5 m either must be deployable or must be constructed in space. Deployable antennas have more than twice the mass of solid-construction antennas. A 32 GHz (Ka-band) antenna will probably require a surface tolerance of 0.5 mm rms or better.[1] This requirement will increase both the mass and the fabrication cost of the antenna.

Designs for a 15-meter radio antenna have been studied for the QUASAT mission. The surface tolerances of these designs are about 0.5 to 0.8 mm rms and their masses range from 198 kg to 300 kg.[2] The mass of a 10-meter Ka-band antenna has been estimated at 230 kg [1]. The useful ranges of mass models for microwave antennas do not usually extend to 200-meter antennas.

A design control table (DCT) for a TAU Ka-band telemetry link is given in Table 1. This table is based on a DCT for a 1000-AU X-band link given by Jaffe [2] and on a Ka-band link for Cassini given by Dickinson [1], Table 9). Jaffe's link uses a 15-meter transmitting antenna, 40 watts of transmitted power, and a 100-m receiving dish. Assuming a coherent system, his link provides a data rate of 100 bps with a performance margin of 2 dB.

The link in Table 1 assumes a 15 meter transmitting antenna and a 200-meter receiver. "Transmitter losses" (Table 1) include all the antenna efficiency, obscuration, pointing, and line loss factors, taken from Dickinson's link. The transmitter gain was calculated using an antenna efficiency factor of 0.548 (transmitter losses in Table 1), and the space loss was calculated from the usual definition [3].

[1] R. E. Freeland, JPL Applied Technologies Section, private communication, October 1986.

[2] R. E. Freeland, "QUASAT Antenna Technology Study," JPL Internal Document, Jet Propulsion Laboratory, Pasadena, CA, D-3292, Sept. 1986.

The receiver efficiencies and gain were obtained similarly; however, no atmospheric effects were included. These effects would change the "mechanical and other" efficiency factor from 0.769 to 0.677 ([1], Table 9), requiring 130 W of power to maintain a performance margin of 3 dB. This link assumes either that a 200-meter antenna with the efficiencies estimated by Dickinson for improved DSN receiving antennas can be built in orbit, or that a ground-based array of Ka-band receiving antennas is used.

The noise spectral density was taken from Jaffe's paper and assumes an effective noise temperature of 25 K. It may be possible to lower the thermal noise further by using cryogenic amplifiers on a space-based receiver ([2] p. 16).

The total received power is the product of RF output power, transmitter gain, space loss and receiver antenna gain in the table.

Jaffe gives the threshold $ST/N_0$ (a measure of the required signal-to-noise ratio) for his link based on a bit error rate of $10^{-4}$ and he computes the ratio of data power to total power received (data power/total power, Table 1) from $(2R_D/(100B_L + 2R_D))$, where $R_D$ is the data rate and $B_L$ is the loop bandwidth ([2], p. 16). A similar calculation was used in Table 1. The threshold data power is the sum of noise spectral density, data rate, and threshold, and the performance margin is then the difference between received data power and threshold data power.

Given a 15-meter transmitter and a 200-meter receiver, 115 watts of DC transmitter power are required to support a data rate of 20 kbps. With a 10-meter transmitter 260 W would be required.

### B. Requirements for an Optical Telemetry Link

A DCT for an optical-frequency TAU telemetry link is given in Table 2. This table was calculated using an optical communications link analysis program written by W. Marshall and B. Burk [4]. The input parameters and the results of the calculations appear in Table 2.

The transmitter for this link uses a 1-meter-diameter telescope and a frequency-doubled Nd:YAG laser emitting at 532 nm. A DC-to-optical power efficiency of 8.5% has been demonstrated for a Nd:YAG, and higher efficiencies should be possible with this or other solid-state laser technologies [10]. At an efficiency of 10% the 10-watt laser in this link would require 100 W of DC power.

The receiver for the link in Table 2 is assumed to be a 10-meter-diameter "photon bucket," a non-diffraction-limited telescope mirror placed in Earth orbit. It is assumed to focus ten times less accurately than would a diffraction limited telescope with the same aperture i.e., the angular diameter of the field of view of a detector at its focus is $10 \times (2.44\,\lambda/D)$. An increased field of view allows the detector to receive more light from extended noise sources and perhaps from more stars, but otherwise has little effect on link performance aside from requiring a larger detector area to collect more light from a larger blur spot.

The detector is assumed to be a cooled avalanche photodiode whose single-photon detection probability ("Detector Quantum Efficiency" in Table 2) is 40%. Such sensitivities for these devices have been demonstrated in the laboratory, but their internal noise increases with sensitivity and may become important for probabilities above about 30% [5]. However, the number of noise photoelectrons generated in the detector will probably not exceed a few hundred to a thousand per second, which is less than $10^{-5}$ electrons per signal pulse. This will have only a small effect on the receiver's performance (see Table 2).

If the transmitter telescope mirror is assumed to be made of beryllium, then its mass may be computed from a model studied by Hughes Aircraft [6]:

$$\text{mass (kg)} = 0.034\,D^{2.7}$$

where $D$ is the mirror's diameter in centimeters. For the 1-meter mirror, this model gives a mass of 55 kg. The validity of this model for mirrors as large as 10 m is not discussed in the Hughes report.

The optics in both the transmitting and receiving systems are assumed to be 65% transmission efficient *in toto*. This does not include a narrow-band interference filter in the receiving optics. Interference filters with a 10-angstrom bandwidth and 65% peak transmittance are presently available.

The telemetry link uses pulse position modulation (PPM) with a word size of 1024, a data rate of 20 kbps, and a bit error rate of $10^{-4}$. A Reed-Solomon code with a coding fraction of 1/2 is assumed and the data rate and error rate values in the table have been adjusted for coding.[3]

Using the input parameters in Table 2, Marshall and Burk's link analysis program calculated a performance margin of 3.1 dB. The expected primary noise sources have been included and are discussed in the next section.

[3]W. K. Marshall, JPL Internal Document, Jet Propulsion Laboratory, Pasadena, CA, Interoffice Memorandum 331-86.6-202, August 1, 1986.

# III. Optical Communication Link Design Considerations

## A. Sources of Optical Noise

The most significant noise source for both the uplink and downlink of a TAU communications system will be sunlight. A useful data rate cannot be maintained if the sun is in the field of view of either the detector on TAU or the receiver at Earth. If TAU remains in the plane of the ecliptic, direct sunlight will interfere with the both links when the earth is in occultation with the sun. However, the earth and sun will be in occultation only 0.5% of the time, and the sun's disk can be in TAU's detector field of view only if the spacecraft trajectory lies within about an arc second of the plane of the ecliptic.

Stray light, light received by the detector from off the optical axis of the receiver telescope, may be a problem when the solar disk lies near, but not in the detector field of view. A telescope's ability to reject off-axis light is strongly dependent on its particular design. Analyses of existing designs which may be similar to the TAU communications telescope will be useful in evaluating the importance of stray light in detail.

Light from discrete stars was not found to be a significant noise problem for stars dimmer than 7th magnitude. The irradiance of the star included in the optical link DCTs was calculated using a brightness temperature close to that of the sun; thus, the bolometric magnitude of this star is little different from its visual magnitude. With a 7th magnitude star in the detector's field of view, a link performance margin of over 2 dB was still possible. A margin of 3 dB or more was obtained in links with stars of 8th magnitude or dimmer.

The mean number density of stars brighter than magnitude 8.0 is 0.56 stars per square degree. The mean density is about 1.1 for low galactic latitudes (averaged over all galactic longitudes) [7]. It should not be difficult to avoid these brightest stars when choosing the exact trajectory for TAU.

The zodiacal light (or "zodi"), sunlight scattered from interplanetary matter in the solar system, was also found not to represent an important noise source. However, if TAU's trajectory lies in or near the plane of the ecliptic, the zodi will appear at or near its maximum brightness in the field of view of the downlink receiver whenever the receiver must be pointed toward the sun to receive signals from TAU. The zodi has therefore been included in the link noise calculations near its maximum brightness. A plot of the spatial distribution of the zodiacal light within the ecliptic is shown in Fig. 1 [8].

Background noise from integrated starlight (ISL) was not found to be a problem for the telemetry link, even when taken at its maximum brightness in the galactic plane. The approximate maximum brightness of the integrated starlight is indicated on the graph in Fig. 1 [9].

Zodi and ISL were not both included in the noise calculations because only the least likely trajectory for TAU would allow a large contribution from both sources. The plane of the ecliptic intersects the galactic plane at about 60° and the line of intersection of the two planes lies close to a vector from the sun to the center of the galaxy. Thus the only TAU trajectory along which both planes could be viewed is one toward or away from the galactic center. But the best trajectories for astrometry are those normal to a vector from the sun to the galactic center, and TAU will probably fly along one of these.

Cherenkov radiation resulting from the interaction of cosmic rays with TAU's receiving optics should produce only negligible noise in the receiver on TAU, since all internal components must be shielded from cosmic rays for other reasons, and the detector and optics will not be exposed. Only a few photons per second (or less) will reach the detector from cosmic ray interactions in the primary mirror of the receiver telescope.

In the uplink, the sunlit earth will always be in the field of view of TAU's detector. (The earth and GEO are only about 0.24 microrad apart as seen from 1000 AU and TAU's detector field of view is 1.3 microrad.) If TAU stays in the ecliptic, the received noise power from the sunlit earth will vary between zero and its maximum value (Earth at inferior conjunction), which was used in Table 3. If TAU stays in the galactic plane (60° out of the ecliptic) the noise will vary between 1/3 and 2/3 of its maximum.

The noise power given in Tables 2 and 3 should not be compared directly with the value of the average received signal power shown on the line above it. The signal power is concentrated in very short pulses whereas the background power is distributed randomly in time.

## B. Optical Uplink

The system requirements for an optical command link for TAU are less stringent than those for a telemetry link, primarily because the required command data rate is less than 1 kbps and because mass and power budgets should allow a more powerful laser and a larger telescope for sending command data.

A DCT for a TAU optical uplink is shown in Table 3. The TAU spacecraft will use the same telescope for reception and transmission. Note that the same wavelength was used in these calculations as was used for the downlink, though this is not necessarily a requirement and may even be undesirable. The Earth orbiting communication station is assumed to transmit from a 1.5 meter telescope (diffraction limited) using a 16-watt laser. The efficiencies of the optics and the detector are assumed to be identical to those used in the downlink calculations, and the expected major noise sources are included at their maximum magnitudes.

This link assumes a PPM word size of 128, a bit error rate of $10^{-4}$, and a command data rate of 500 bps. Reed-Solomon coding is assumed, with a coding fraction of 7/8; the adjusted data rate and error rate values are shown in the tables. The operational parameters were selected to give a performance margin of about 3 dB. Different parameters e.g., a larger word size, can provide a greater margin and would allow a less powerful laser or smaller transmitter aperture. A data rate of 500 bps is probably not necessary for transmission of command data to TAU; 32 bps has been given as a command data rate for Galileo [3]. Such a reduction in data rate would reduce considerably the command link parameter requirements.

## C. Acquisition and Tracking

From 1000 AU the earth and sun are separated by 1 millirad (maximum) and TAU's communication telescope will have an angular limit of resolution of less than 1 microrad. However, an imaging detector (e.g., a CCD array) with a dynamic range of 90 dB or more would be required to image both objects simultaneously. The difference in brightness will be even greater when the sunlit earth is seen at less than its maximum brightness.

A more suitable beacon than the sunlit earth would be the uplink communication laser itself. The peak power received by the spacecraft from a 16-watt pulsed laser is greater than the received background power from the sun, even when the sun fills the detector's field of view behind the beacon. The laser energy received by TAU from a 16-watt laser operating with a duty cycle of $270 \times 10^{-6}$ ("on" for 270 $\mu$sec each second) would be approximately equal to the solar background received through a narrow-band filter in the same time interval, about 3 picojoules. Much smaller duty cycles, and therefore higher peak powers, are easily attainable.

This calculation assumed a small nonimaging detector (as did the communications link calculations), but a CCD detector should be able to image both the laser beacon and the sun in the background through a neutral density filter.

## IV. Conclusion

The TAU mission would provide an opportunity for a number of astronomical and space science experiments that could not be carried out inside the solar system. This study examined the problem of returning to Earth the data obtained by TAU and found a communications system based on optical frequencies to be more practical for the TAU mission than one based on radio frequencies. Although the technology for optical communications is still much less mature than radio frequency communications technology, an optical system can meet the requirements of TAU without any technological breakthroughs – the necessary development can be reasonably expected before the time TAU is to be launched.

# References


[1] R. M. Dickinson, "A Comparison of 8.415-, 32.0-, and 565646-GHz Deep Space Telemetry Links," *JPL Publication 85-71*, Jet Propulsion Laboratory, Pasadena, CA, pp. 20, Oct. 15, 1985.

[2] L. D. Jaffe, et al., "An Interstellar Precursor Mission," *J. British Interplanetary Soc.*, vol. 33, pp. 3-26, 1980.

[3] J. H. Yuen, "Telecommunications Systems Design," *Deep Space Telecommunications Systems Engineering*, J. Yuen, ed., pp. 1-22. Plenum Press, NY, 1983.

[4] W. K. Marshall and B. D. Burk, "Received Optical Power Calculations for Optical Communications Link Performance Analysis," *TDA Progress Report 42-87*, vol. July-September 1986, Jet Propulsion Laboratory, Pasadena, CA, pp. 32-40, Nov. 15, 1986.

[5] D. L. Robinson and B. D. Metscher, B. D. "A Cooled Avalanche Photodiode with High Photon Detection Probability," *TDA Progress Report 42-87*, vol. July-September 1986, Jet Propulsion Laboratory, Pasadena, CA, pp. 41-47, Nov. 15, 1986.

[6] Hughes Aircraft Co., Final Report of A Study to Determine the Impact of Laser Communication Systems on Their Host Spacecraft, prepared for NASA Goddard Space Flight Center under Contract NAS 5-27139, April 1984, Section 9.

[7] C. W. Allen, *Astrophysical Quantities*, 3rd edition, The Athlone Press, University of London, p.243, 1981.

[8] C. Leinert, C. " Zodiacal Light – A Measure of the Interplanetary Environment," *Space Sci. Rev*. vol. 18, pp. 281-339, 1975.

[9] F. E. Roach and R. R. Megill, "Integrated Starlight Across the Sky," *Ap. J.*, vol. 133, p. 128, 1961.

[10] D. L. Sipes, "Nd:YAG End Pumped by Semiconductor Laser Arrays for Free Space Optical Communication," *IEEE Military Communications Conference*, Boston, MA, pp. 104-108, Oct. 20-23, 1985.

**Table 1. TAU Ka-band telemetry link**

| | | | |
|---|---|---|---|
| Wavelength (m) 0.009369 (32 GHz) | | | |
| Range (AU, m) 1000 1.49e14 | | | |
| Transmitter | | dB | Ref. |
| Antenna diameter, m | 15 | | (1) |
| DC power, W, dBm | 115 | 50.6 | |
| DC-to-RF conv. efficiency | 0.21 | -6.8 | (2) |
| RF output power, W, dBm | 24.15 | 43.8 | |
| Losses | 0.548 | -2.6 | (2) |
| Gain, dB | 1.385e7 | 71.4 | |
| Space loss, 1000 AU | 2.5e-35 | -346.0 | |
| Receiver | | | |
| Antenna diameter, m | 200 | | |
| RF efficiency fraction, dB | 0.871 | -0.6 | (2) |
| Mechanical and other efficiencies | 0.769 | -1.1 | (2) |
| Antenna gain | 3.009e9 | 94.8 | |
| Noise spectral density, dBm/Hz | | -185.0 | (1) |
| Total received power, W, dBm | 2.5e-17 | -136.0 | |
| Data channel | | | |
| Data rate, BPS, dB BPS | 20000 | 43.0 | |
| Bit error rate | 0.0001 | -40.0 | (1) |
| Data power/total power | | -0.01 | (1) |
| Received data power | | -136.0 | |
| Threshold ST/No | | 3.0 | (1) |
| Threshold data power | | -139.0 | (1) |
| Performance margin | 1.99 | 3.0 | |

Table 2. Optical communications link analysis

| | | TAU Downlink | Factor | dB |
|---|---|---|---|---|
| Wavelength, micrometers | = | 0.53200 | | |
| PPM Parameters (Coded) | | | | |
| Alphabet size, M | = | 1024.0 | | |
| Data rate, Kbits/sec | = | 40.039 | | |
| Dead time, microseconds | = | 239.52 | | |
| Slot width, nanoseconds | = | 10.000 | | |
| Required link bit error rate | = | 0.15000 | | |
| Laser output power, watts | | | 10.0 | 40.0 dBm |
| Min Req'd peak power, watts | = | 0.25E+06 | | |
| Transmitter antenna gain | | | 0.247E+14 | 133.9 |
| Antenna dia., meters | = | 1.000 | | |
| Obscuration dia., meters | = | 0.200 | | |
| Beam width, microrad | = | 0.920 | | |
| Transmitter optics efficiency | | | 0.650 | -1.9 |
| Transmitter pointing efficiency | | | 0.946 | –0.2 |
| Bias error, microrad | = | 0.050 | | |
| RMS jitter, microrad | = | 0.050 | | |
| Space loss, 1000.00 AU | | | 0.801E–43 | –431.0 |
| Atmospheric transmission factor | | | 1.00 | 0.0 |
| Receiver antenna gain | | | 0.335E+16 | 155.2 |
| Antenna dia., meters | = | 10.000 | | |
| Obscuration dia., meters | = | 2.000 | | |
| Field of view, microrad. | = | 1.298 | | |
| Receiver optics efficiency | | | 0.650 | -1.9 |
| Narrowband filter transmission | | | 0.650 | -1.9 |
| Bandwidth, angstroms | = | 10.000 | | |
| Received signal power, watts | | | 0.172E–13 | -107.6 dBm |
| Noise sources | | | | |
| Zodi, radiance, W/m$^2$ Sr Å | = | 0.10000E-07 | | |
| 8th mag. star irradiance, W/m$^2$ Å | = | 0.15000E-14 | | |
| Recv'd background power, watts | = | 0.478E–12 | | |

**Table 2. (contd)**

| | | TAU Downlink | Factor | dB |
|---|---|---|---|---|
| Detector Quantum efficiency | | | 0.400 | -4.0 |
| Photons/joule | | | 0.268E+19 | 154.3 dB/mJ |
| Detected signal PE/second | | | 0.184E+05 | 42.7 dB/Hz |
| Symbol time, seconds | | | 0.250E-03 | -36.0 dB/Hz |
| Detected signal PE/symbol | | | 4.61 | 6.6 |
| Required signal PE/symbol | | | 2.25 | 3.5 |
| Detected background PE/slot | = | 0.512E-02 | | |
| Margin | | | 2.05 | 3.1 |

**Table 3. Optical communications link analysis**

| | | TAU Uplink | Factor | dB |
|---|---|---|---|---|
| Wavelength, micrometers | = | 0.53200 | | |
| PPM parameters (coded) | | | | |
| Alphabet size, M | = | 128.00 | | |
| Data rate, Kbits/sec | = | 0.57200 | | |
| Dead time, microseconds | = | 12225.0 | | |
| Slot width, nanoseconds | = | 100.00 | | |
| Required link bit error rate | = | 0.12000E-01 | | |
| Laser output power, watts | | | 16.0 | 42.0 dBm |
| Min Req'd peak power, watts | = | 0.20E+07 | | |
| Transmitter antenna gain | | | 0.556E+14 | 137.5 |
| Antenna dia., meters | = | 1.500 | | |
| Obscuration dia., meters | = | 0.300 | | |
| Beam width, microrad | = | 0.614 | | |
| Transmitter optics efficiency | | | 0.650 | -1.9 |
| Transmitter pointing efficiency | | | 0.885 | -0.5 |
| Bias error, microrad | = | 0.050 | | |
| RMS jitter, microrad | = | 0.050 | | |
| Space loss, 1000.00 AU | | | 0.801E-43 | -431.0 |
| Atmospheric transmission factor | | | 1.00 | 0.0 |
| Receiver antenna gain | | | 0.335E+14 | 135.2 |
| Antenna dia., meters | = | 1.000 | | |
| Obscuration dia., meters | = | 0.200 | | |
| Field of view, microrad. | = | 1.298 | | |
| Receiver optics efficiency | | | 0.650 | -1.9 |

**Table 3. (contd)**

| | | TAU Uplink | Factor | dB |
|---|---|---|---|---|
| Narrowband filter transmission | | | 0.650 | -1.9 |
| Bandwidth, angstroms | = | 10.000 | | |
| Received signal power, watts | | | 0.580E-15 | -122.4 dBm |
| Noise sources | | | | |
| Sunlit Earth at 1000 AU | | | | |
| Zodi, radiance, $W/m^2$ Sr A | = | 0.10000E-07 | | |
| 8th mag. star, irradiance, $W/m^2$ A | = | 0.15000E-14 | | |
| Recv'd background power, watts | = | 0.510E-14 | | |
| Detector Quantum efficiency | | | 0.400 | -4.0 |
| Photons/joule | | | 0.268E+19 | 154.3 dB/mJ |
| Detected signal PE/second | | | 621.0 | 27.9 dB/Hz |
| Symbol time, seconds | | | 0.122E-01 | -19.1 dB/Hz |
| Detected signal PE/symbol | | | 7.60 | 8.8 |
| Required signal PE/symbol | | | 3.85 | 5.9 |
| Detected background PE/slot | = | 0.546E-03 | | |
| Margin | | | 1.97 | 3.0 |

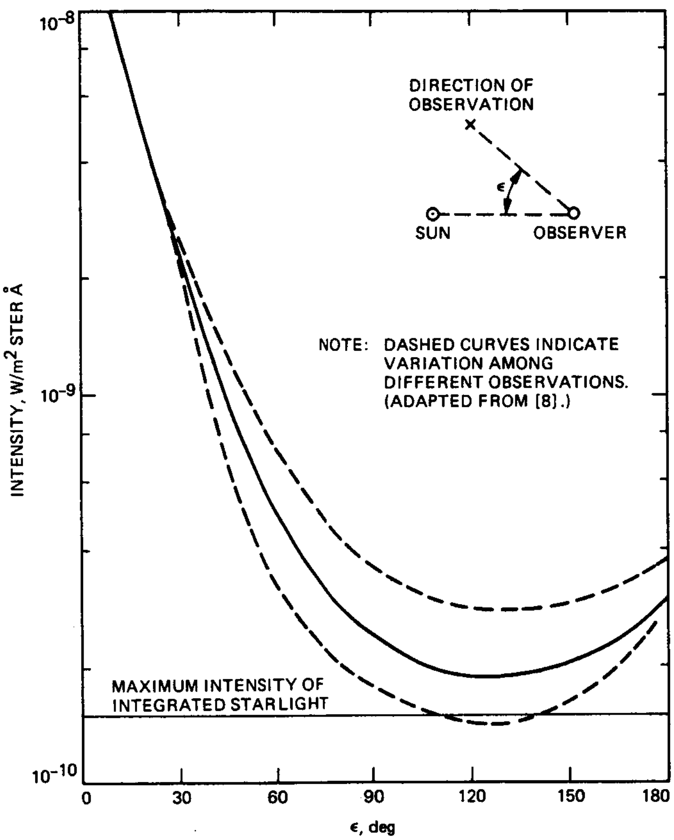


**Fig. 1. Intensity of the zodiacal light in the ecliptic**