Multipurpose Interplanetary Laser Instrument

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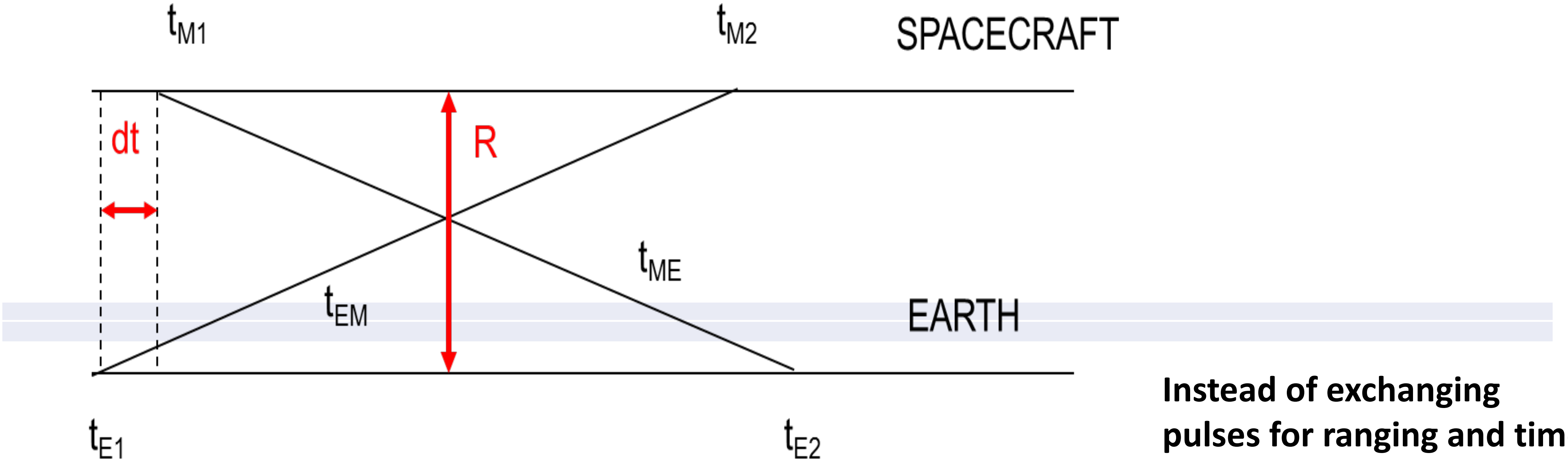
Asynchronous Laser Transponder for Interplanetary Ranging and Time Transfer

J.J. Degnan, J. Geodynamics **2002**, *34*, 551–594.

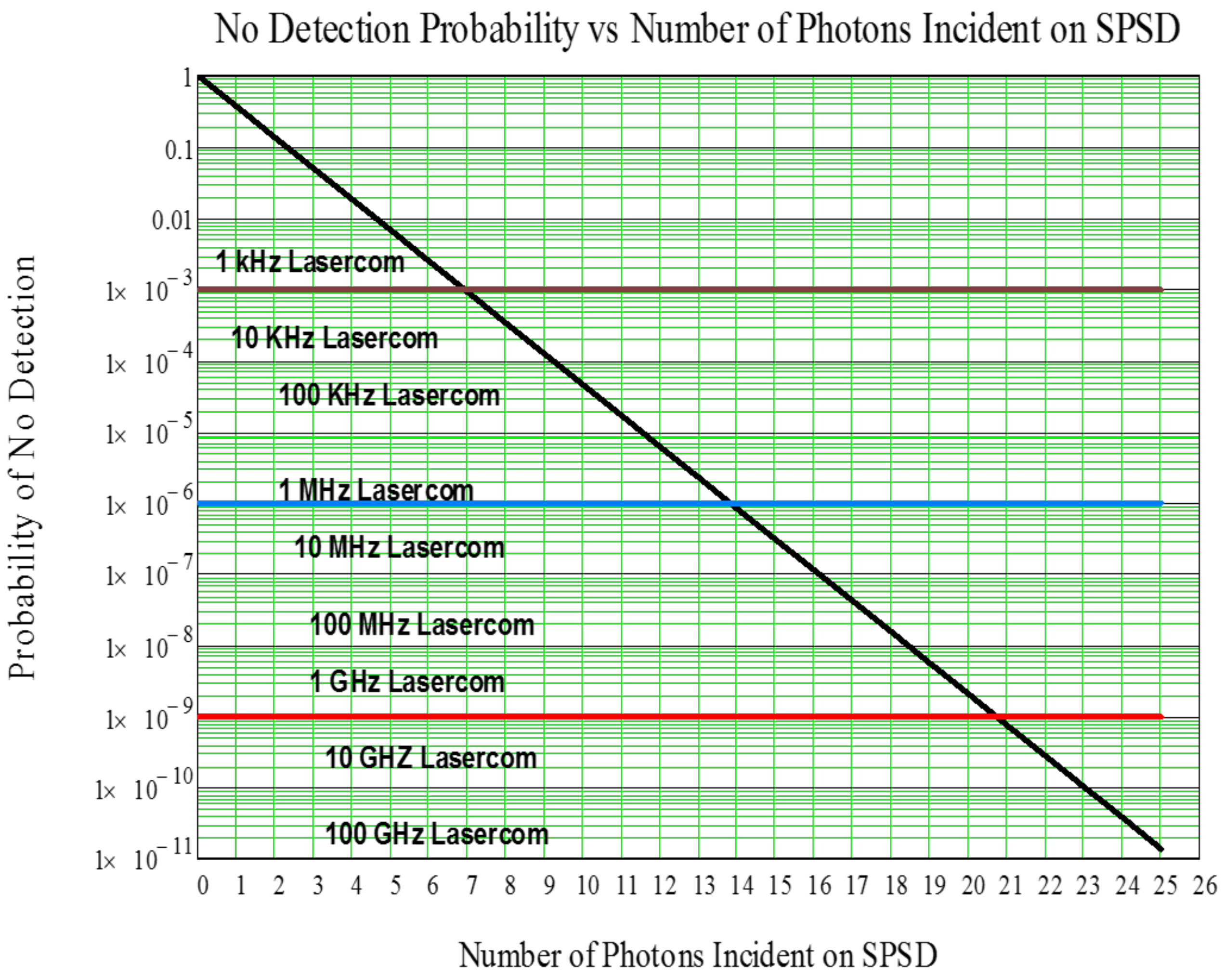


Range $R = c(t_{ME} + t_{EM})/2 = c\,[(t_{E2}-t_{E1})+(t_{M2}-t_{M1})]/2$

Clock Offset $dt = [(t_{E2}-t_{E1})-(t_{M2}-t_{M1})]/[2(1+R/c)]$

Instead of exchanging pulses for ranging and time transfer, the two-way communications link can send codes providing the time the codes were sent from each terminal.

No Detection Probability vs Number of Photons Incident on Single Photon Detector



Note that

- **7 photons per bit results in a Bit Error Rate (BER) of 1 per 1000,**
- **14 photons per bit results in a BER of 1 per million, and**
- **21 photons per bit results in a BER of 1 per billion.**

EXAMPLE: OOK LASERCOM SYSTEM

.J. J. Degnan, Photonics, 2023, 10, 98

- **On-Off-Keying (OOK) is a simple communications code that uses a combination code of ones and zeros to transmit information from one destination to another. In ranging or time transfer mode, the code could convey the station clock time at the start of the code.**
- **From the previous graph, if you wanted no more than one bit error per thousand (Kbps), one per million (Mbps), or one per billion (Gbps), the desired number of received photons per bit would be 7, 14, and 21.**
- **The number of photons transmitted by the laser per second would be equal to :7 thousand for a 1 Kbps sytem, 14 million for a 1 Mbps system, and 21 billion for a 1Gbps system.**
- **Multiplying the number of photons per second by the photon energy hc/λ yields the required laser power.**
- **The code could be transmitted by either modulating a CW beam or switching pulses out of a stream of Q-switched (Mbps) or modelocked (Gbps) laser pulses.**
- **In the presence of background or internal noise, one can assign a threshold number of photons per bit below which the signal is assigned a “zero”**

Interplanetary Link Equation

J.J. Degnan, Photonics, 2023, 10, 98

The number of photons per bit received by the Earth station is given by

$$n_{rE} = n_{tP}\eta_{tP}G_{tP}G_{rE}\eta_{rE}\eta_{dE}R_{PE}^{-2}$$

where
n_{tP} = the number of photons per pulse/bit emitted by the planetary laser
$\acute{\eta}_{tP}$ = the optical efficiency of the planetary transmit optics
G_{tP} = the transmitter gain of the planetary telescope (optical antenna)
G_{rE} = the receiver gain of the Earth telescope (optical antenna)
η_{rE} = the optical efficiency of the Earth receive optics
η_{dE} = the optical efficiency of the Earth detector
R_{PE} = range between the Earth and planetary terminals

The corresponding equation for the Earth to planet optical link is obtained by interchanging the *E* and *P subscripts* in the above equation.

Maximum Transmitter Optical Antenn

B.J. Klein & J. Degnan, Applied Optics, 1974, 13. 2134-2141.

$$G_T = \frac{4\pi A_T}{\lambda^2} g_T\left(\alpha_T, 0, \gamma_T, 0\right)$$

$$= \frac{4\pi A_T}{\lambda^2} \frac{2}{\alpha_T^2}\left\{\exp\left(-2\alpha_T^2\right) + \exp\left(-2\alpha_T^2\gamma_T^2\right)^{-} - 2\exp\left[-\alpha_T^2\left(1+\gamma_T^2\right)\right]\right\}$$

$A_t = \frac{\pi D_P^2}{4}$ is the area of the telescope primary miror

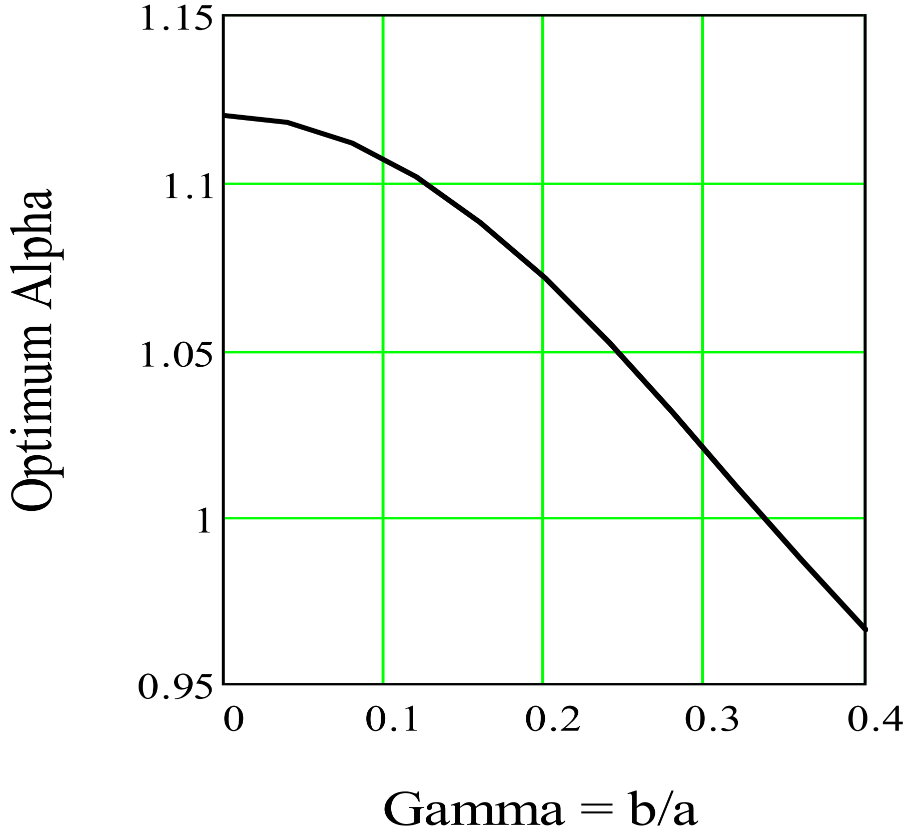
λ is the laser wavelength

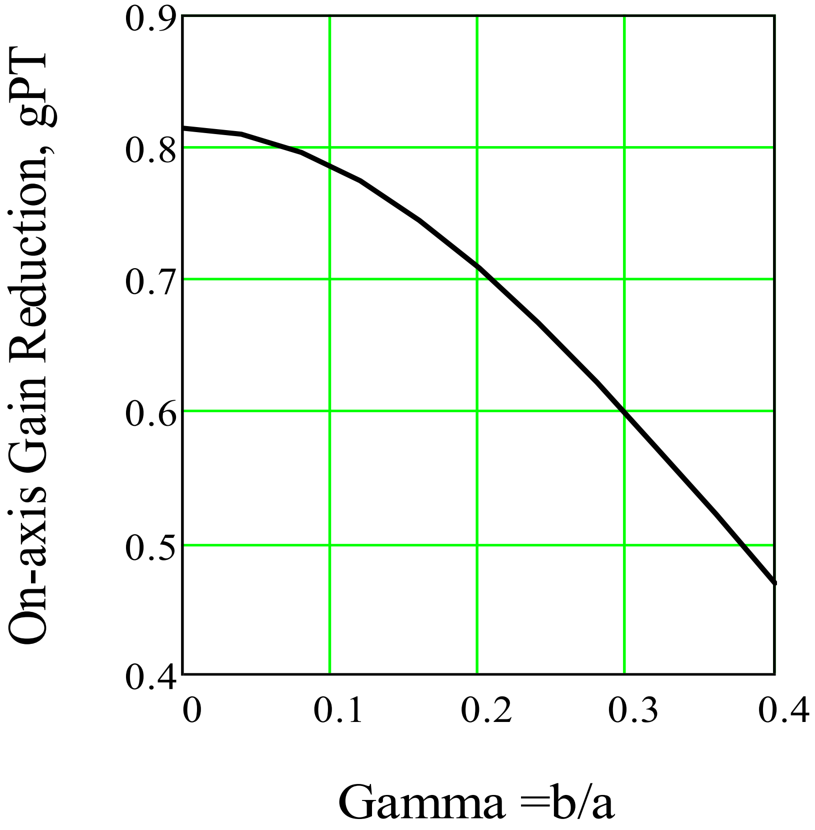
α_T = 1.12-1.30γ_T^2+2.12γ_T^4

$\gamma_T = \frac{D_S}{D_P}$ = ratio of the secondary and primary mirror diameters

Maximizing the Far Field Gain of the Transmitting Antenna

B.J. Klein & J.J. Degnan, Applied Optics, 1974, 13. 2134-2141.





The left hand graph gives the ratio of the primary mirror radius to the laser Gaussian beam radius, i.e., $\alpha_T = a_T/\omega$, which yields maximum on-axis far field gain as a function of the secondary mirror obscuration ratio $\gamma_T = b_T/a_T$. The second graph shows the resulting reduction in the peak far field transmitter gain relative to $4\pi A_T/\lambda^2$ where A_T is the area of the primary mirror.

$\alpha_T^{opt} = 1.12 - 1.30\gamma_T^2 + 2.12\gamma_T^4$

$G_R = A_R\left(1-\gamma_R^2\right)\eta_{RD}$

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Receiver Optical Antenna Gain

J.J. Degnan & B.J. Klein , Applied Optics, 1974, 13, 2397-2401.

The gain of the receive telescope is given by

$$G_R = A_R\left(1-\gamma_R^2\right)\eta_{RD}$$

where

A_R is the area of the receive telescope primary mirror

γ_R is the ratio of the secondary and primary mirror diameters and

η_{RD} has a maximum value of 0.95 if $\pi R_D/\lambda F_E > 0.7$ where R_D is the detector radius, and F_E is the Earth telescope F-number, i.e., the ratio of the receive telescope focal length over the primary diameter

Interplanetary Link Equation

J.J. Degnan, Photonics, 2023, 10, 98

If we multiply both sides of the Equation on slide 5 by the photon energy $h\nu$ and the desired bit frequency f_b, we generate the equation for the transmitted laser power from the planetary platform needed to generate the desired number of received photons per bit at the Earth station, i.e.,

$$P_{tP}(D_{tP}D_{rE})^2 = P_{rE}(\lambda R_{PE})^2 \frac{4}{\pi^3 \eta_{tot}\eta_{dE} g_{tP}(1-\gamma_{rE}^2)}$$

In the Equation above, P_{rE} is the desired received power at the Earth station. For example, if we want to limit the Bit Error Rate (BER) to one per thousand in a KHz system, one per million in a MHz system, or one per billion in a GHz system, then, based on the graph in slide 3 , the desired laser power received at the Earth terminal, P_{rE} is equal to the photon energy $h\nu$ multiplied by the desired received photons per bit n_{rE} and the bit frequency f_b, e.g., 7 thousand (KHz), 14 million (MHz), or 21 billion (GHz).

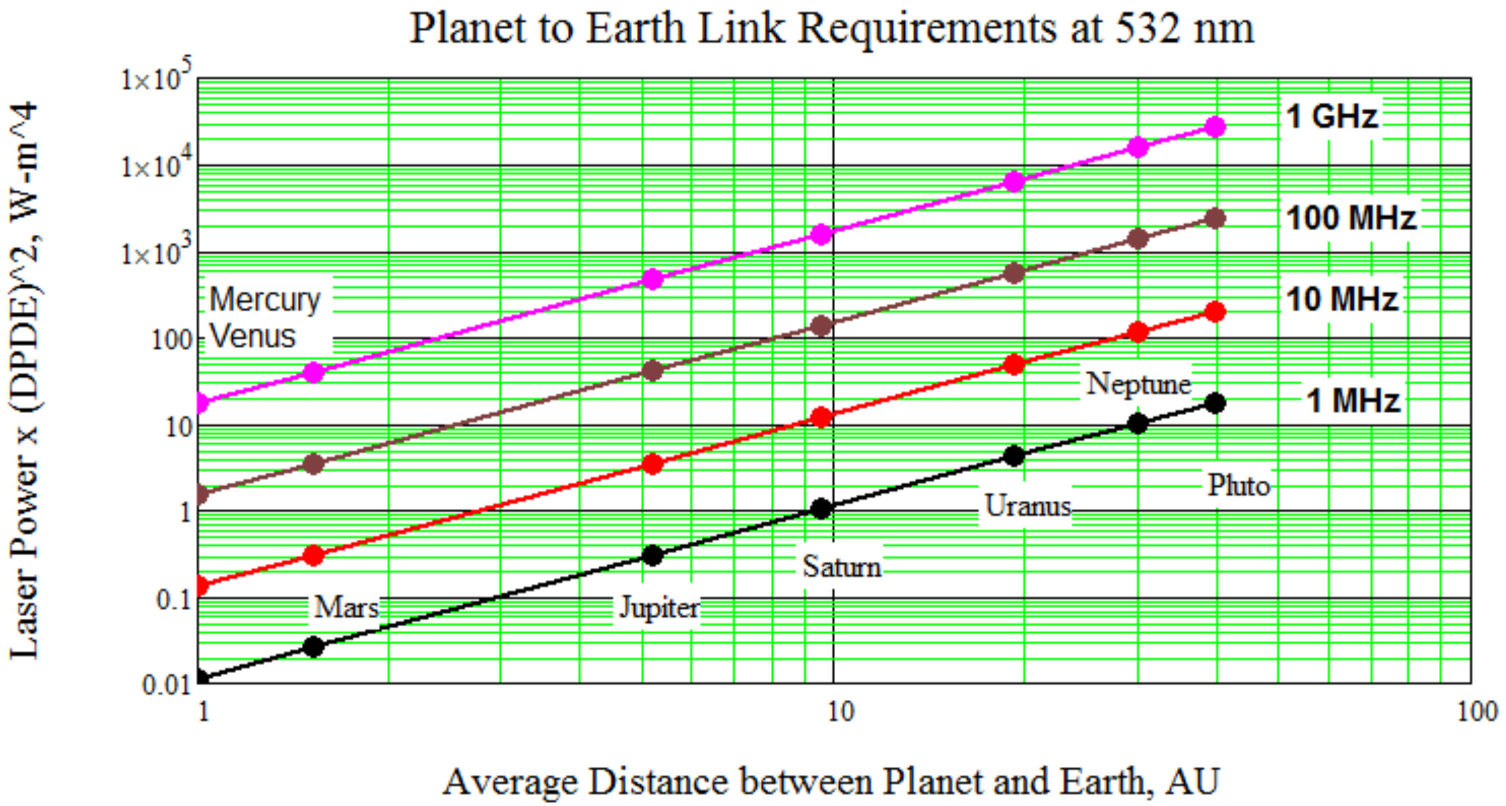
Relevant Planetary Characteristics

J.J. Degnan, *Photonics*, 2023, 10, 98

	Solar Distance (AU)	Planet Diameter (km)	Planet Orbital Period (years)	Planet Rotational Speed (km/hr)	Mean Earth to Planet Distance (AU)	Mean One-Way Light Transit Time (min)	Mean Planet Angular Radius (µrad)	Mean Earth Angular Radius (µrad)
Mercury	0.38	4,879	0.2	10.83	1	8.3	16.42	40.93
Venus	0.72	12,104	0.6	6.52	1	8.3	40.73	42.93
Earth	1.00	12,758	1.0	1,574	0	0	NA	NA
Mars	1.52	6,792	1.9	866	1.52	12.6	15.04	28.24
Jupiter	5.2	142,984	11.9	45,583	5.2	43.0	92.52	8.25
Saturn	9.54	120,536	29.5	36,840	9.54	78.8	42.51	4.50
Uranus	19.2	51,118	84	14,794	19.2	158.6	8.96	2.24
Neptune	30.1	48,528	164.8	9,719	30.1	248.3	5.43	1.43
Pluto	39.5	2,376	248	47.18	39.5	326.3	0.20	1.09

Interplanetary Link Equation for λ =532 nm*

J.J. Degnan, *Photonics*, 2023, 10, 98



Example

P=20W	DE*DP=1m2
Mercury	1 Gbps
Venus	1 Gbps
Mars	800 Mbps
Jupiter	80 Mbps
Saturn	20 Mbps
Uranus	8 Mbps
Neptune Pluto	2 Mbps 1 Mbps

The product of the transmitted laser power emitted by the planetary probe and the two telescope diameters squared (y-axis) is plotted as a function of the planetary distance (x-axis) for a wavelength of 532 nm and four candidate bit rates: 1 MHz (black), 10 MHz (red), 100 MHz (brown), and 1 GHz (pink). The dots along the lines indicate the average distance of the planet from Earth, as listed in Slide 10.

*** The chart can be used for other wavelengths by multiplying the *y*-axis number by $(\lambda/532\ \mathrm{nm})^2$.**

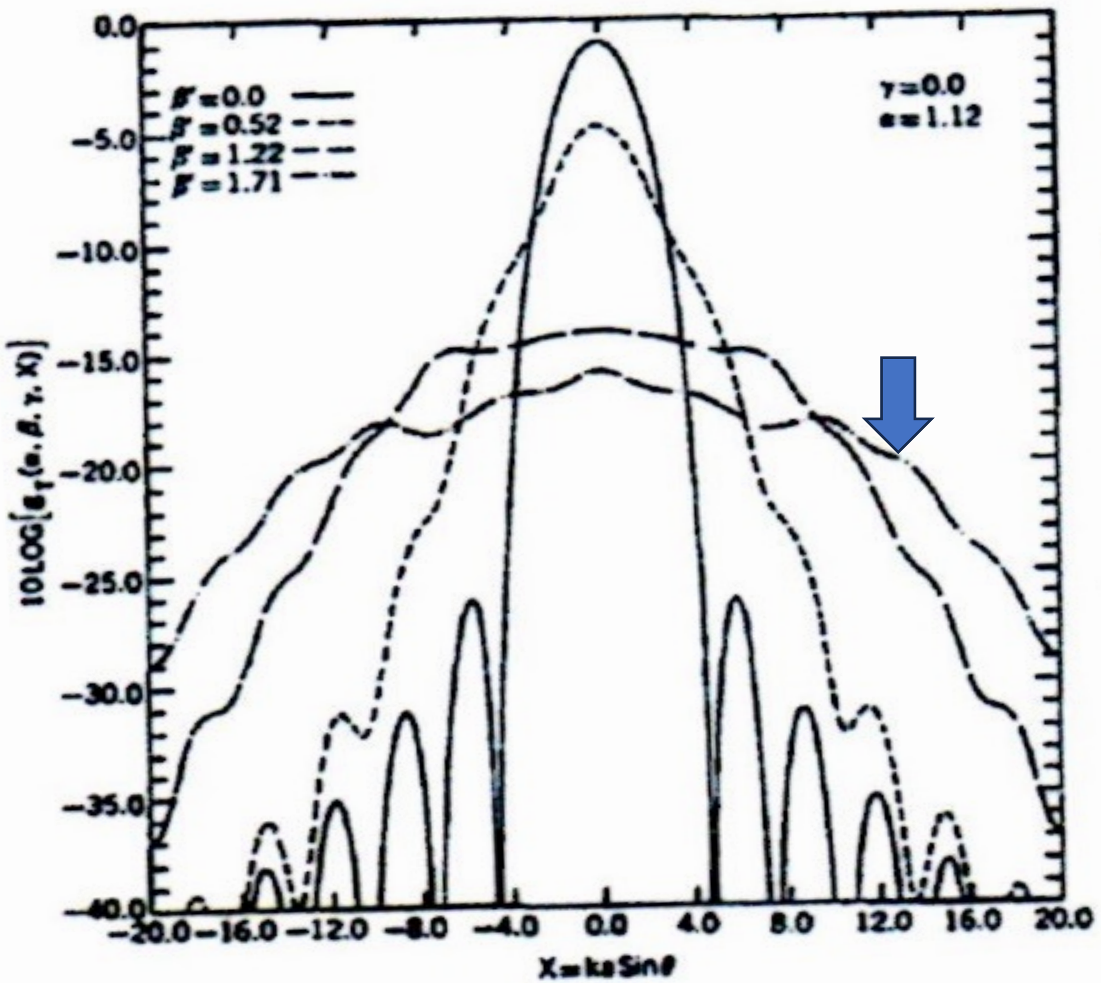
Opposite Terminal Acquisition and Tracking

Although narrow laser beamwidths on the order of a few microradians greatly reduce the laser power and telescope diameters needed to transmit high data rates between Earth and other planets in the solar system, they also complicate the initial acquisition and tracking of the opposite terminal due to:

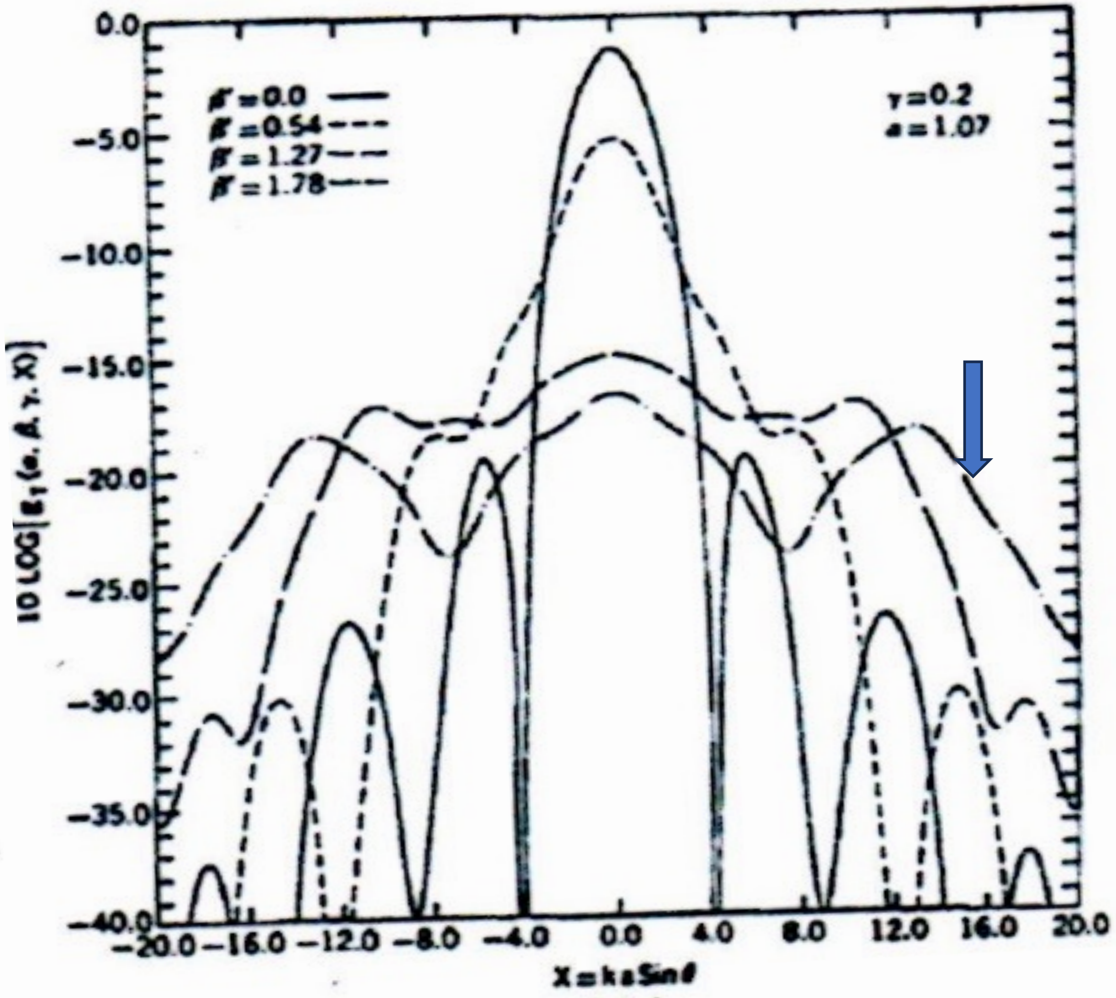
1. **The distance between the Earth and its sister planets (40 AU for Pluto) and the finite speed of light requiring accurate point ahead angles during opposite terminal acquisition.**
2. **Even if the sunlit planet can be seen by the telescope, the angular size of the planets as viewed from Earth and vice versa, listed in slide 10, is, except for the outermost planets, typically much larger than the angular spread of the laser beam (a few microradians). However, the angular search area can be greatly reduced to a narrow band about the planet if the satellite is placed in a polar orbit.**

FAR FIELD TRANSMITTER PATTERNS
with and without defocusing γ = 0 and γ = 0.2

B. J. Klein & J.J. Degnan, Applied Optics , 1974, 13. 2134-2141

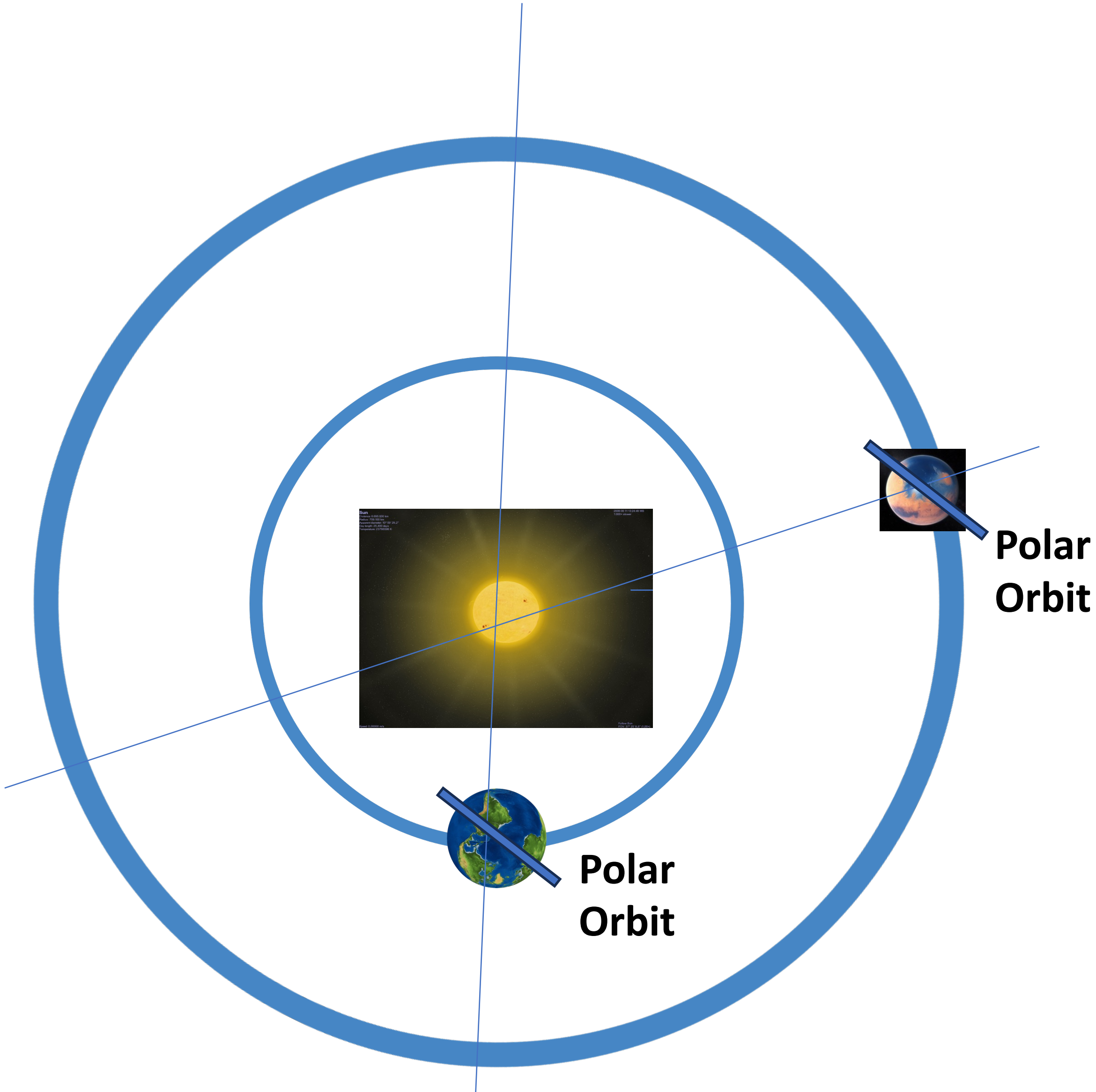


5 (a)



6 (a)

LASER COMMUNICATIONS LINK

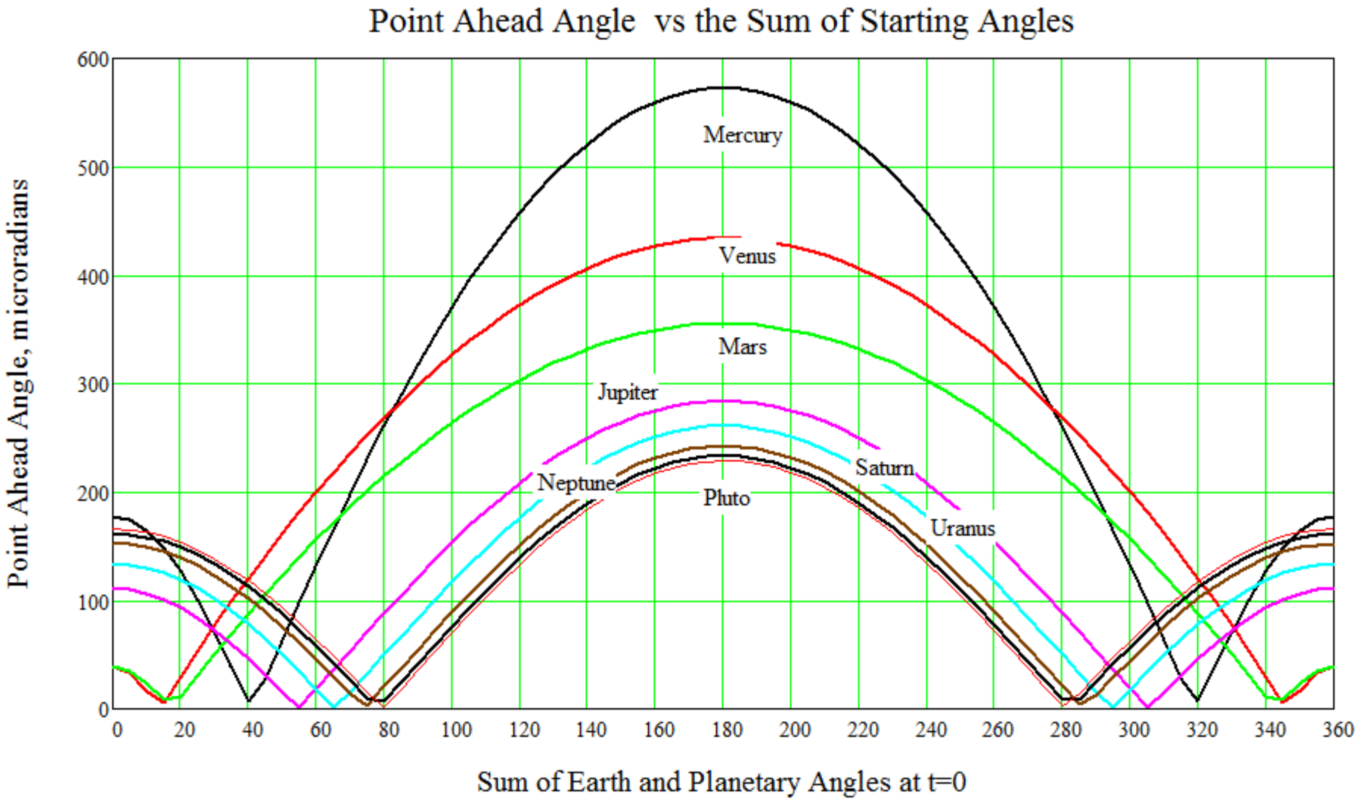


- Unlike ground terminals, having both satellites in polar orbits about their planets eliminates frequent interruptions in data streaming caused by planetary rotations about their axes, weather, or cloud cover
- Planetary polar orbit gives total access to surface and atmosphere for optimum science studies
- Earth polar orbit provides near-continuous line of sight to planetary satellite and uninterrupted communications for extended periods of time
- Earth terminal can use conventional wideband microwave links to download the planetary data to multiple Earth stations under all weather and cloud conditions.
- The use of a serviceable Hubble class 2.2 m telescope permits high bandwidth communications throughut the solar system using sub-meter diameter planetary telescopes
- In principle, a single planetary instrument design can be extended to the outer reaches of the solar system by increasing the time per bit and accepting a reduction in data rate.

Earth-Planet Point-Ahead Angles vs $(\theta_P+\theta_E)$

J.J. Degnan; Photonics, IEEE, 2023, 10, 98

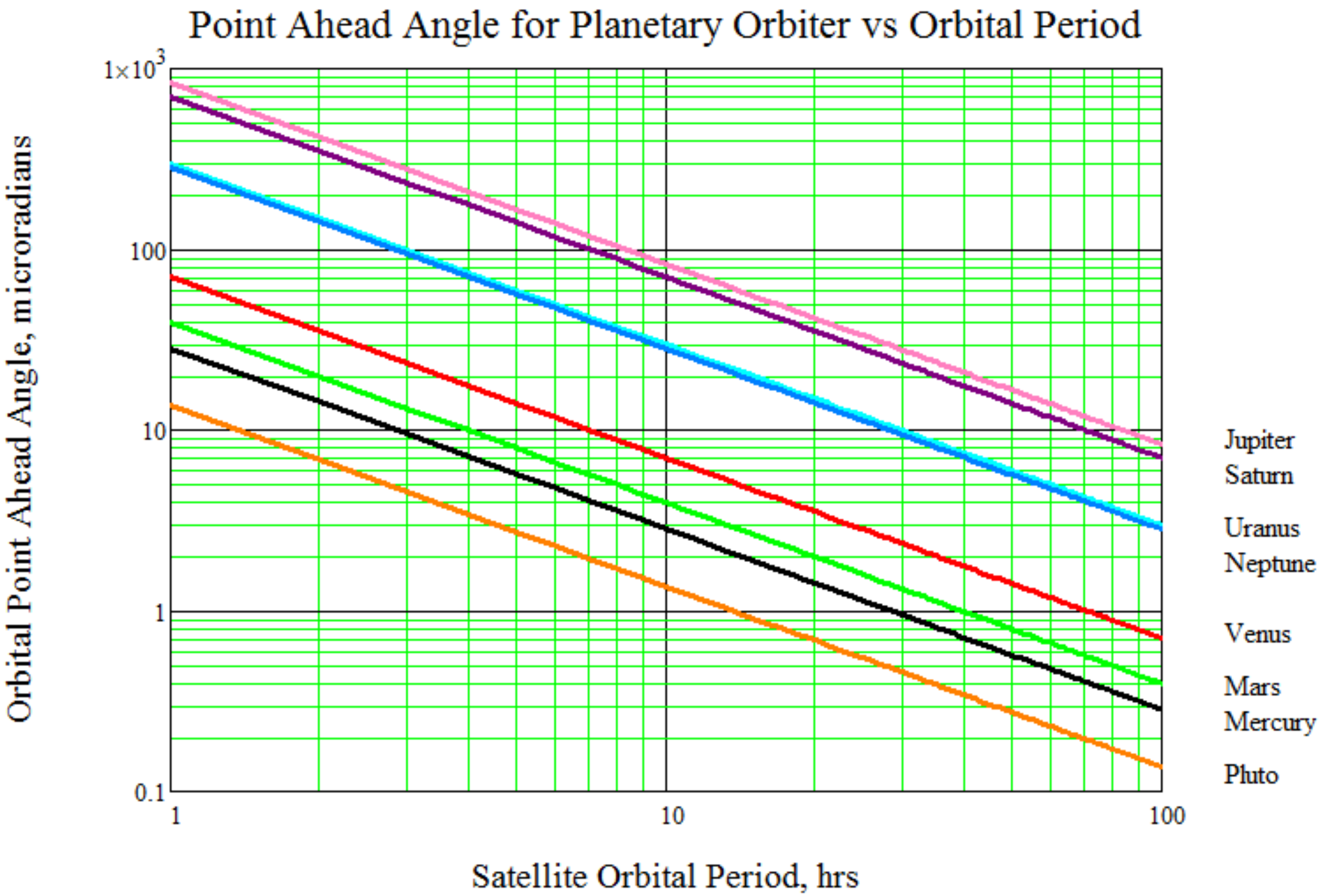
Terminal point ahead angles in microradians for the various planets in the solar system versus the sum of their angular positions in their orbits about the Sun. Maximum point ahead angle occurs when Earth and the planet are on opposite sides of the Sun (180°) due to the fact that: (1) the range between them, and therefore the light travel time, is maximized; and (2) their orbital velocities are in opposite directions and therefore the relative velocity is additive.



The point ahead angles decrease for the outer planets because of their slower orbital angular velocities. Smaller secondary peaks occur at 0° (or 360°) for all the planets because: (1) the orbital velocities are in the same direction and therefore the relative velocity is reduced ; and (2) the light travel time is minimized. Intermediate angles where the point ahead angle drops to near zero would be advantageous for mutual acquisition of the two terminals and occur twice per Earth year.

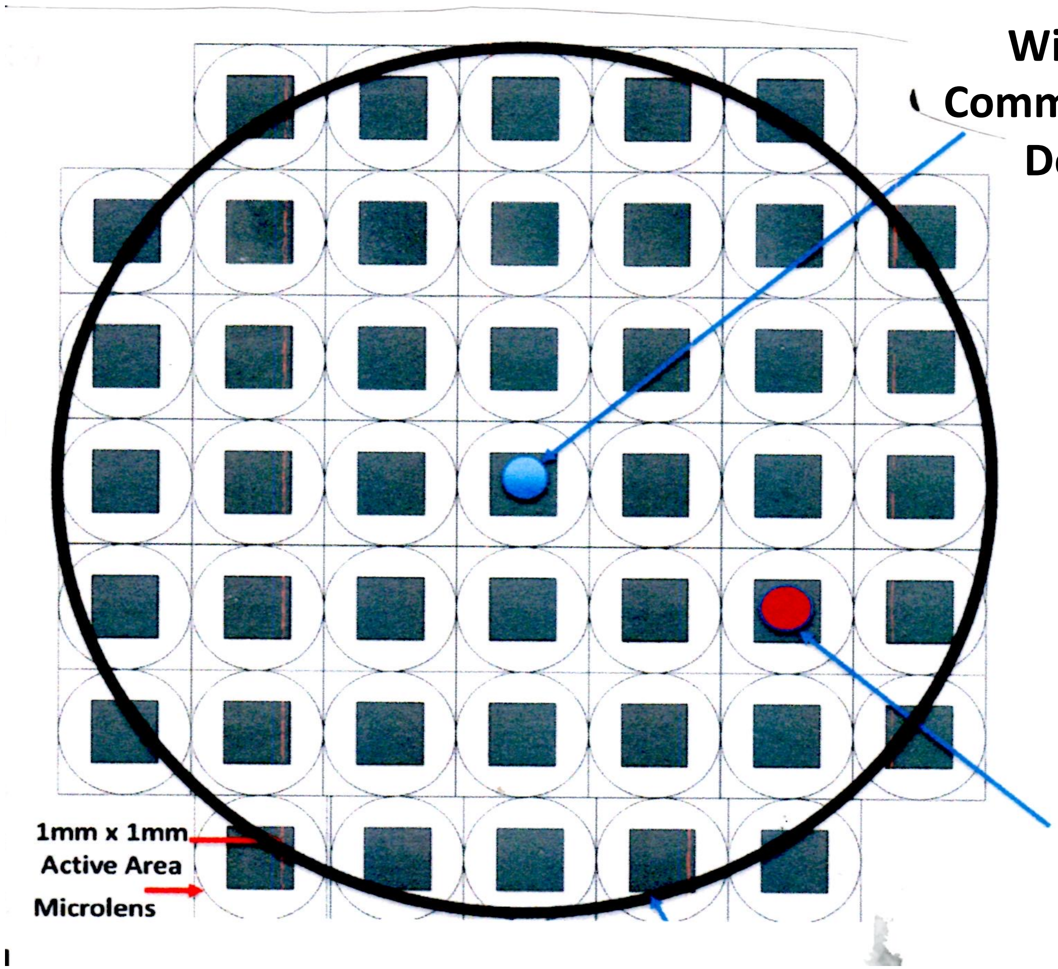
Point Ahead Angle for Planetary Orbiter

J.J. Degnan, Photonics, 2023, 10, 98



- **The planetary orbital velocity introduces another component of transmitter point-ahead that must be accounted for due the narrow transmit beams on the order of a few microradians**
- **Larger planets (e.g. Jupiter and Saturn) require higher angular velocities to complete the orbit within a given time period**
- **Higher orbits are characterized by slower angular speeds and longer orbital periods.**
- **Longer orbital periods aid in the initial acquisition and continued tracking of the terminal.**

Terminal Acquisition and Coalignment Using Modified SGSLR Single Photon Detector Array



Wideband Communications Detector

Time Integrating Acquisition Detector

The proposed optical design of the array detector is similar in concept to the NASA SGSLR detector which consists of 45 detectors equipped with imaging lenses However, in this case, the central detector is dedicated to wideband communications while the others include integrating circuits which aid in initial acquisition of the opposite terminal and maintaining coalignment during wideband communications. The 8 pixels nearest to the central pixel integrate over 100 bit periods while the more extreme pixels integrate up to 1000 bit periods to compensate for signal strength losses when the telescopes are defocused to accelerate the terminal coalignment process. (See Slide 13).

Testing the Instrument with Existing Satellites

J.J. Degnan, Lasers, Clocks, and Drag Free Control, Springer, 2008, pp. 231-243.

Satellite	Altitude (km)	Mean Target Cross-Section 10^6 m^2	Minimum Transponder Range (AU)	Maximum Transponder Range (AU)
LAGEOS	6,000	15	0.263	0.771
GLONASS	19,000	55	1.38 Mercury/Venus	2.72 Mars
GPS	20,000	19	2.60	5.06 Jupiter
LRE) (elliptical)	25,000	2	12.52	23.12 Uranus
Apollo 15 (Moon)	384,000	1,400	111.6 Beyond Pluto	

SUMMARY

- **Wideband communications (1 Mbps to 1 Gbps) between Earth and all of the planets in the solar system is possible with modest laser powers (tens of Watts) and submeter planetary telescopes communicating with a nominal 2.2 m telescope (e.g. the NASA Hubble) in polar Earth orbit.**
- **Polar orbit for the planetary probe provides science access to the entire surface and atmosphere while a polar orbit for the Earth terminal provides access to global microwave antennas for data downloads unhindered by the Earth atmosphere or clouds**
- **Polar orbits for both terminals: (1) greatly extends the time interval during which wideband communications can be carried out ; (2) reduces the angular search area for initial acquisition of the opposite terminal. However, communications must be suspended at least twice per year due to solar interference (i.e. when $\theta E+\theta P =0$ or 180 degrees).**
- **Initial acquisition of the opposite terminal is aided by observation of the sunlit planet, preferably at a time of year when the point-ahead angle is at or near zero, which occurs twice per Earth year.**
- **Initial coalignment of the Earth and planetary terminals is aided by defocusing the telescopes at the two stations to increase the angular spread of the transmit beam by a factor of 50 and using single photon sensitive array detectors (e.g. 7x7) where the central detector is dedicated to wideband communications and the remaining pixels integrate over multiple “bits” (typically 100 to 1000) to detect and guide the terminals into coalignment before refocusing and initiating communications.**
- **The 8 time-integrating pixels closest to the central communications pixel can detect small misalignments and quickly drive the systems back into coalignment.**