Optical Communication in Space -
A Challenge to Microwave Links

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Abstract:

Laser communications offer a viable alternative to microwave communications for intersatellite and interplanetary links. Main characteristics are higher data rates, small size antenna telescopes with narrow beamwidths, but the drawback of the necessity for complex pointing, acquisition and tracking systems.
After a review of some important technology aspects and modulation / detection schemes the optospecific link parameters axe discussed. An experimental coherent optical system set-up at DLR is described.

1. Introduction

Today, space communication is exclusively based on microwave links. Under the stress of RF spectrum management and the increasing demand for a data transfer at higher data rates it became evident that the potential of data transmission in the optical frequency range by lasers must be considered. An additional advantage in space projects is the smaller antenna size onboard a spacecraft requiring less additional weight and volume. Blockage of the field of view for satellite sensors and momentum disturbances are diminished. Fewer on-board consumables for attitude control will be required.
The diameter of the Voyager antenna, e.g. is 3.7 meters. During the Saturn encounter the footprint in the plane of the earth of the X-band signal was 2000 times the earth's diameter. A laser at Saturn transmitting visible light of say 0.5 µm wavelength through a 10 cm telescope would produce a footprint like the diameter of the earth only.
A considerable drawback of those kind of systems is the demand for a high-precision acquisition and tracking system and the raised degree of system complexity.

2. Applications of optical space communication systems

The potential use of optical communication systems can be divided in three main applications (Fig. 1):

- Interorbit link: Of great interest is the data transmission from a low earth orbit (LEO), such as earth ressources satellites, manned spaced stations, polar platforms or Hermes to a geostationary earth orbit (GEO), or a data relay satellite (DRS). This data link requires high data rates in the order of 500 Mb/s in the return link (LEO-GEO), while the forward link (GEO - LEO) only demands telemetry data rates of about 25 Mb/s.

- Intersatellite link: A second important application especially for commercial voice, television and data transmission is an intersatellite link between two geostationary telecommunication satellites. This link prevents double hopping arising from the use of an additional third earth station if two participants living on opposite sides on the earth like to communicate. Moreover interferences with microwave links will be avoided.
  Deep space missions: A third application of prime importance is the high capacity data transmission from planets such as Mars (78 to 400 million kilometers from earth) or Saturn (1197 to 1654 million kilometers from earth) to a geostationary earth DRS.

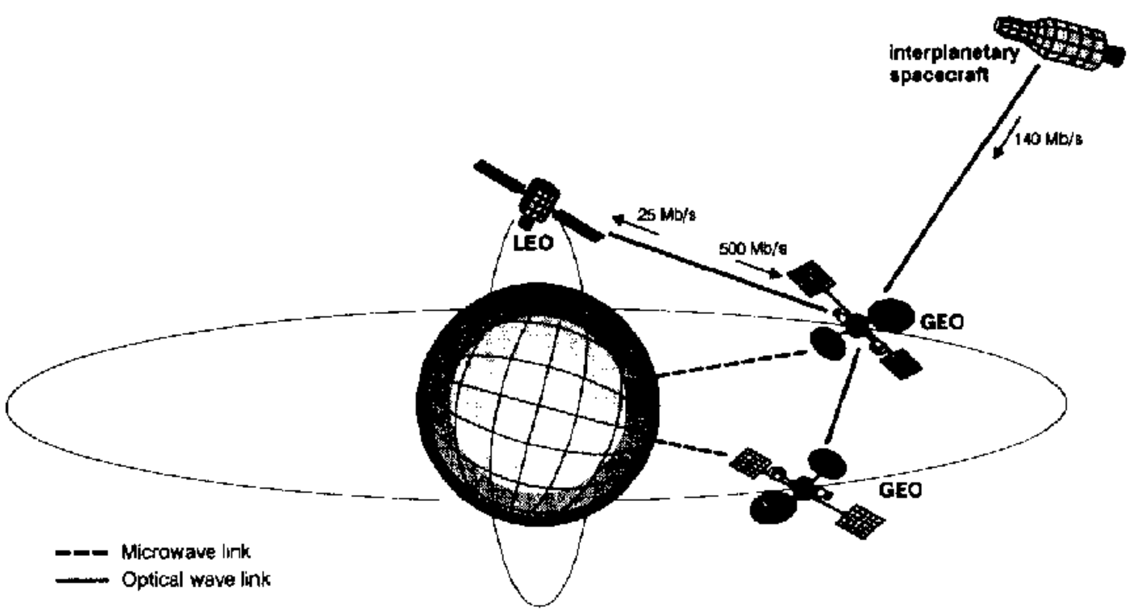

Fig. 1: Potential optical Space Communication Links

3. Technology Aspects

3.1 Laser Transmitters

Because of the requirement for both high efficiency and high beam quality many lasers which are suitable in terrestric applications are unsuitable for long-distance space communications. The most common solid-state lasers employ optical pumping of a host crystal or glass dopped with an appropriate ion. The best developed materials are ruby, Nd^{3+}: glass and Nd^{+3}: YAG (Y_3 A_{15} 0_{12}).

The Neodym-doped:Yttrium-Aluminium Garnet (Nd: YAG) Laser is the most commonly used solid-state type at present, which possesses a combination of properties uniquely favorable for laser operation.

The YAG host is hard, of good optical quality and has a high thermal conductivity. The cubic structure favours a narrow fluorescent linewidth, resulting in high gain and low threshold. Its structure is stable in a wide operational temperature range. Strength and hardness are lower than ruby but still good enough for normal fabrication procedures.

Approximately 2W continuous operation have been achieved from a diode pumped Nd: YAG rod laser in a single fundamental coherent node of 1.06 µm with a conversion efficiency of 13 % /l/.

Further development efforts being made to obtain 10 W c.w. output. In some applications the frequency is doubled in a nonlinear crystal (e.g. $KTiOPO_4$) with more than 50 % efficiency, resulting in a quantum detection efficiency of higher than 30 %. Furthermore the doubled frequency experiences only 1/2 the diffractive spreading of the fundamental frequency.

3.2 Detector Features

For communication links based on semiconductor laser diodes or Nd: YAG lasers the detector of choice is an avalanche photodiode, which is operated in the photoconductive mode with internal gain by virtue of the avalanche multiplication process. They show best response at shorter wavelengths, but at longer wavelengths InGaAs and Ge-avalanche diodes are the favoured materials.

Fig. 2 demonstrates the quantum efficiency of different photodiodes where the incident photons are converted to electrons. The mean output current is proportional to the quantum efficiency. The output of the detector is input to a preamplifier which converts the detector signal current into a voltage for further signal processing. The preamplifier noise effects the systems sensitivity, of course. It is typically specified as a noise current spectral density at the preamp input in A/√Hz.

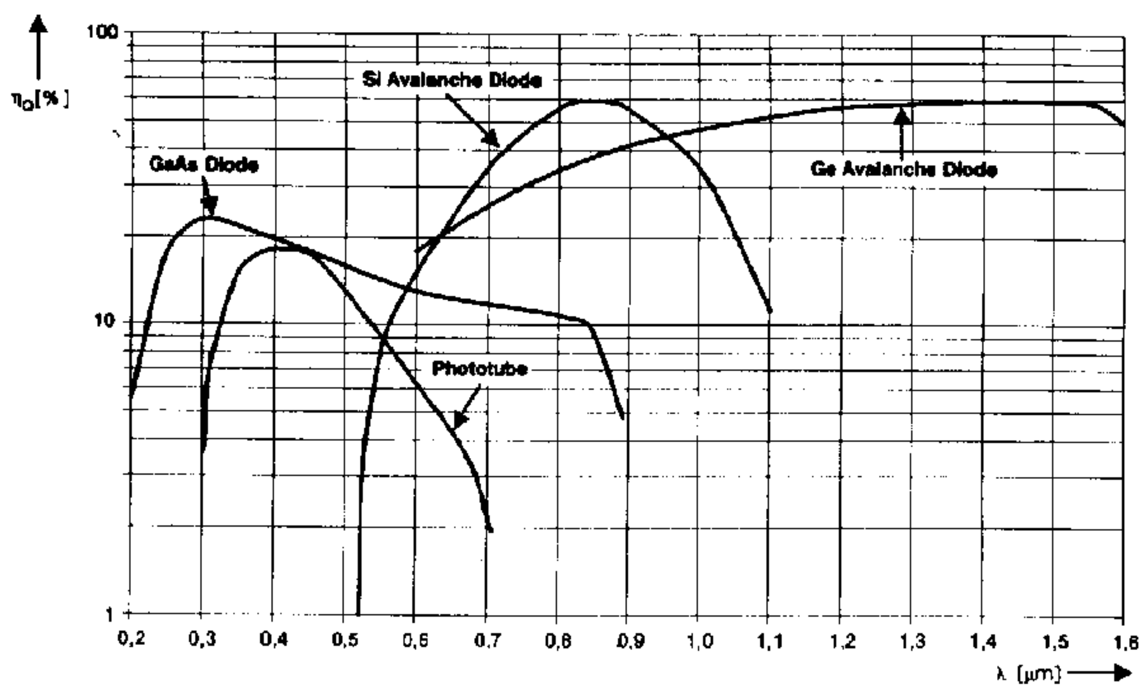

Fig. 2: Quantum Efficiency of Photodiodes

The angular sensitivity for a tracking detector is a function of the physical size, the field of view, the received signal spot size and its intensity distribution.

3.3 Modulation and Demodulation Techniques

Pulse modulation is the most commonly used format to transmit digital data in direct detection systems. The simplest way is to intensity-modulate between 2 levels corresponding to 0 and 1. Realized pulse modulation formats use on-off keying (OOK), Pulse Position Modulation (2-PPM, 4-PPM, 8-PPM) and bipolar polarisation modulation (BPM). In the M-ary timeslot PPM formats (M=2, 4, 8...) the bit stream is coded in each data word. This technique leads to a very low duty-cycle, e.g. with a 8-PPM format the laser is on for less than 0.4 % of time. Minimum turn-on time can be as low as 1 ns. The laser source may operate in a multiple longitudinal incoherent mode with typical spectral widths from 1 to 10 nm.

The received energy is collected and focused on the photodetector, responding only to the carrier intensity changes. Sensitivity limitations are the signal-to quantum noise ratio and the background noise. The signal is amplified so that the output is far over the thermal noise.

In a heterodyne digital transmission system, information is encoded as amplitude, frequency or phase shifts (ASK, FSK or PSK) of the coherent carrier (single longitudinal mode) with typical spectral widths of the order of 10 KHz to 10 MHz.

Frequency modulation (FSK) can be obtained by direct modulation of the laser diode bias current whereas ASK and PSK need an external modulator.

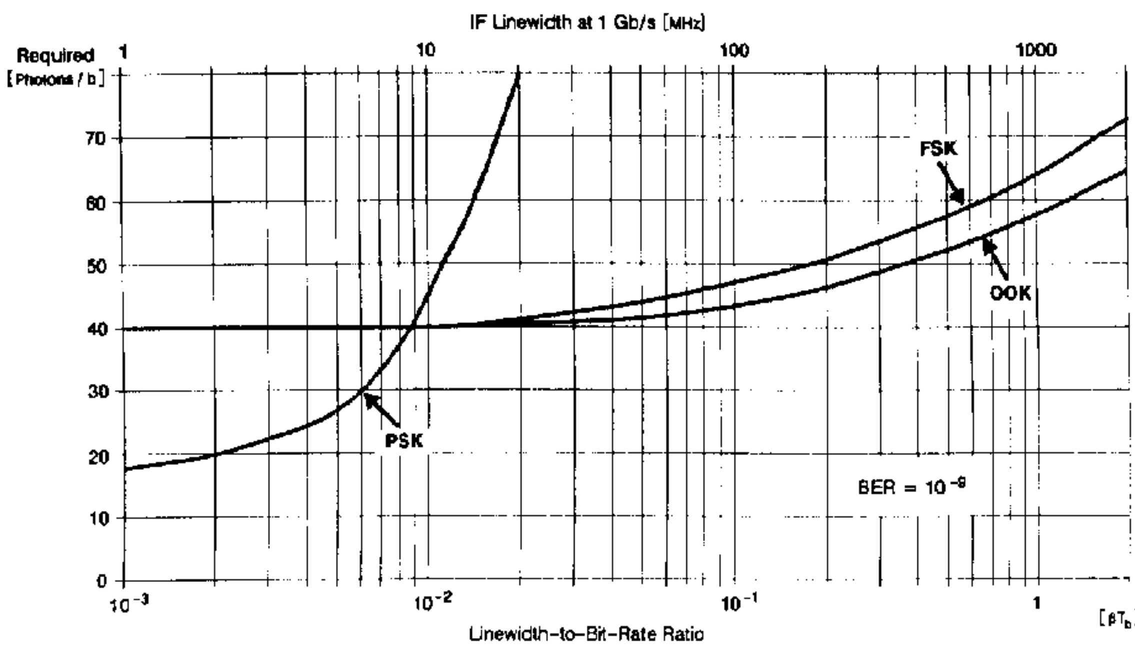

Fig. 3: Quantum-Limited Receiver Sensitivity

In the heterodyne receiver the information-bearing input signal is mixed within an optical fiber coupler with a strong local oscillator (LO)laser and the combined wave is detected using a photodiode. The intermediate frequency signal (IF), the difference between the input signal and the LO is typically arranged to be in the 1 to 10 GHz range. The linewidth of the laser frequency finally limits the efficiency of digital modulation schemes. As can be seen from Fig. 3, coherent PSK gives best performance as long as the linewidth is not greater than 1/1000 of the bit rate, otherwise the sensitivity advantage over DPSK, FSK or even OOK is lost /3/. FSK and OOK can be detected even at a linewidth-to-bitrate ratio of 1, as they are less (FSK) or not (OOK) sensitive to phase noise.

4. Link Analysis

The link budget of a laser communication link may be calculated in a similar way like in microwave links. The free space attenuation for various distances up to interplanetary dimensions is compared with microwave frequencies in Fig. 4. The increase in attenuation is more than compensated by the higher beam directivity in the optical range, as the beam divergence is proportional to the square of the ratio operating wavelength to aperture diameter (D/8). Note, that the wavelength ratio of a 1 cm (30 GHz) microwave source to a 1 µm (300 THz) laser is in the order of 10^4!

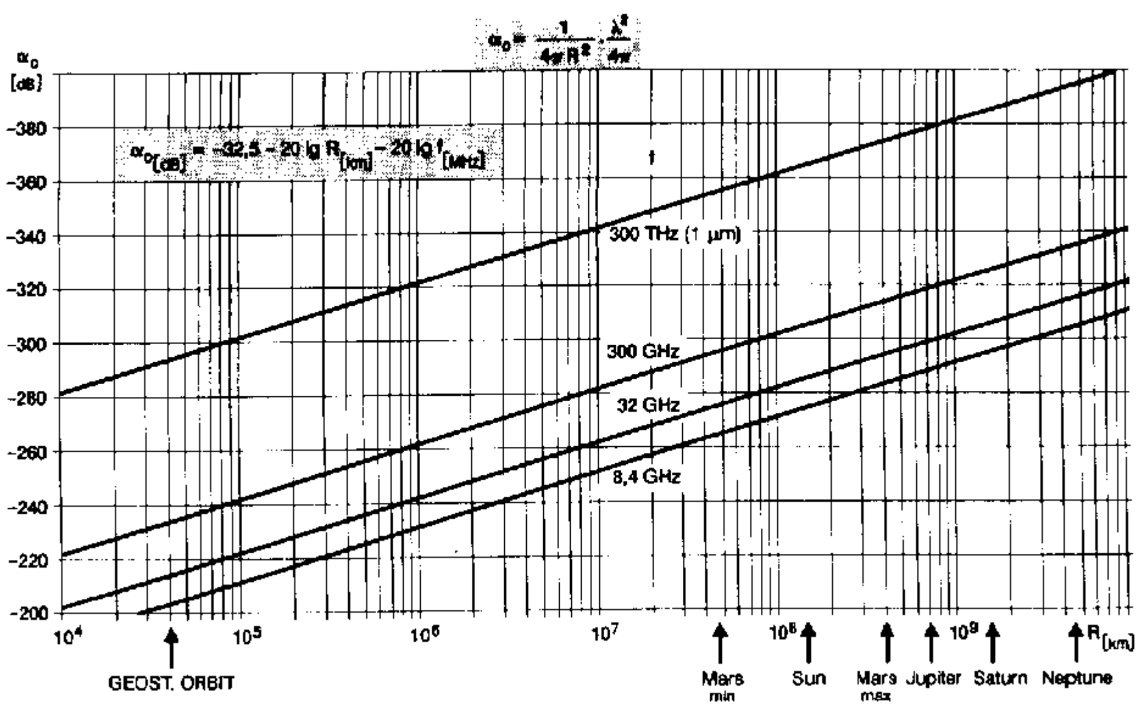

Fig. 4: Free Space Attenuation between Isotropic Radiators

The laser beamwidth is restricted by the diffraction limit of the optics to

$$2_i \leq 1.278_L / D_A \text{ [rad]} \qquad (1)$$

where $_L$ stands for the laser wavelength and D_A for the diameter of the aperture.

The far-field on-axis antenna gain for a Gaussian feed beam is given by

$$G(2_L) = 32 / 2_L^2 \qquad (2)$$

where 2_L is defined as the $1/e^2$ beamwidth (see Fig. 5).

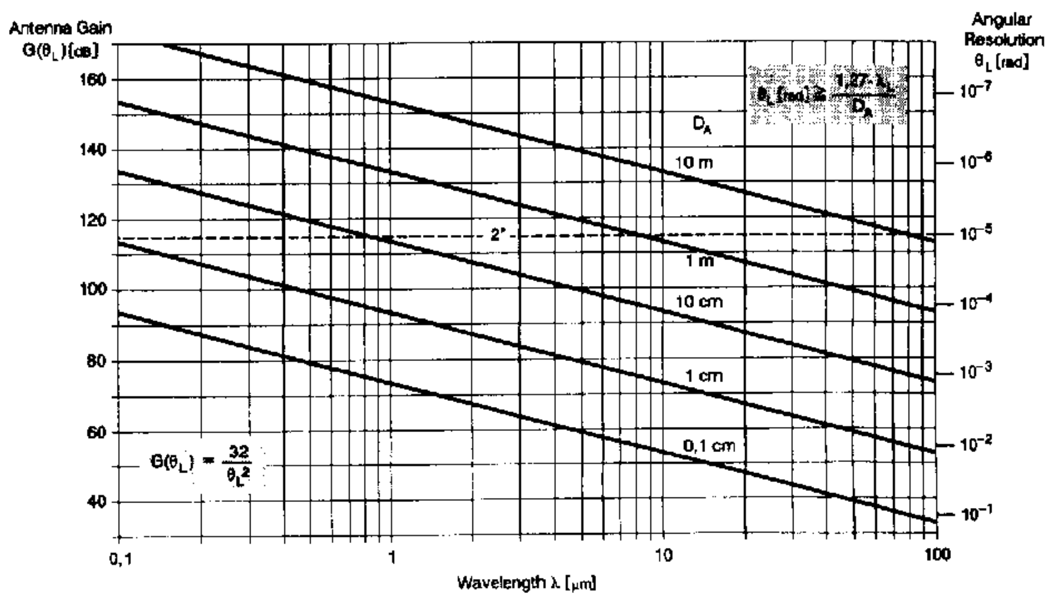

Fig. 5: Angular Resolution and Gain of Antenna Telescopes

Noise characteristics at optical frequencies are significantly different than those at radio frequencies (RF). Fig. 6 demonstrates that thermal noise predominates at RF and quantum noise is unimportant since h·f is much smaller than k·T. The quantum noise is the statistical fluctuation of photons. It increases linearly and is the limiting factor at optical frequencies.

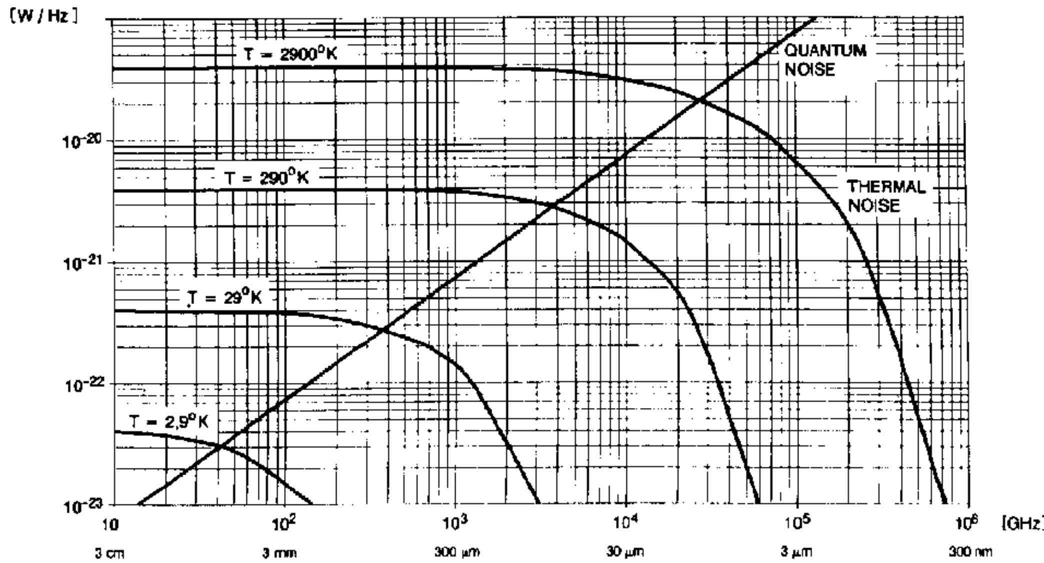

Fig. 6: Quantum- and Thermal Noise

Analogous to microwave systems, instead of the thermal noise k·T the inherent quantum noise may be calculated:

$$N = h \cdot f \cdot B \qquad (3)$$

$h = 6.62 \cdot 10^{-34}$ [Js] Planck's constant

In direct detection receivers with avalanche photodiodes the detection process does not approach the quantum-limit performance. Therefore the thermal noise due to the preamplifier is a significant contributor to the total noise power.

A potential limitation is imposed by any background source like the sun, planets, star clusters, sunlit clouds and scattered sunlight. That kind of noise is reduced by making both the field of view and the spectral width as narrow as possible. The optical width of filters must be compatible with the linewidth of the laser source and of the expected doppler shift, of course.

Receiving stations on ground will be problematic from the operational standpoint, though the opacity of the clear atmosphere in the optical range, especially at the UV-end is fair.

Heterodyne receiving is more challenging because the turbulent atmosphere corrupts the coherence of the signal. In order to overcome obscurations by clouds a multiple-site diversity is under study by selecting several sites separated by a few hundreds kilometers. Such sites with anticorrelated weather patterns are known to exist e.g. in the US (Kitt Peak National Observatory/Arizona and Mt. Wilson/California) /2/.

Future Data Relay Satellites will be equiped with optical systems to allow continuous communications of interplanetary spacecrafts with the earth.

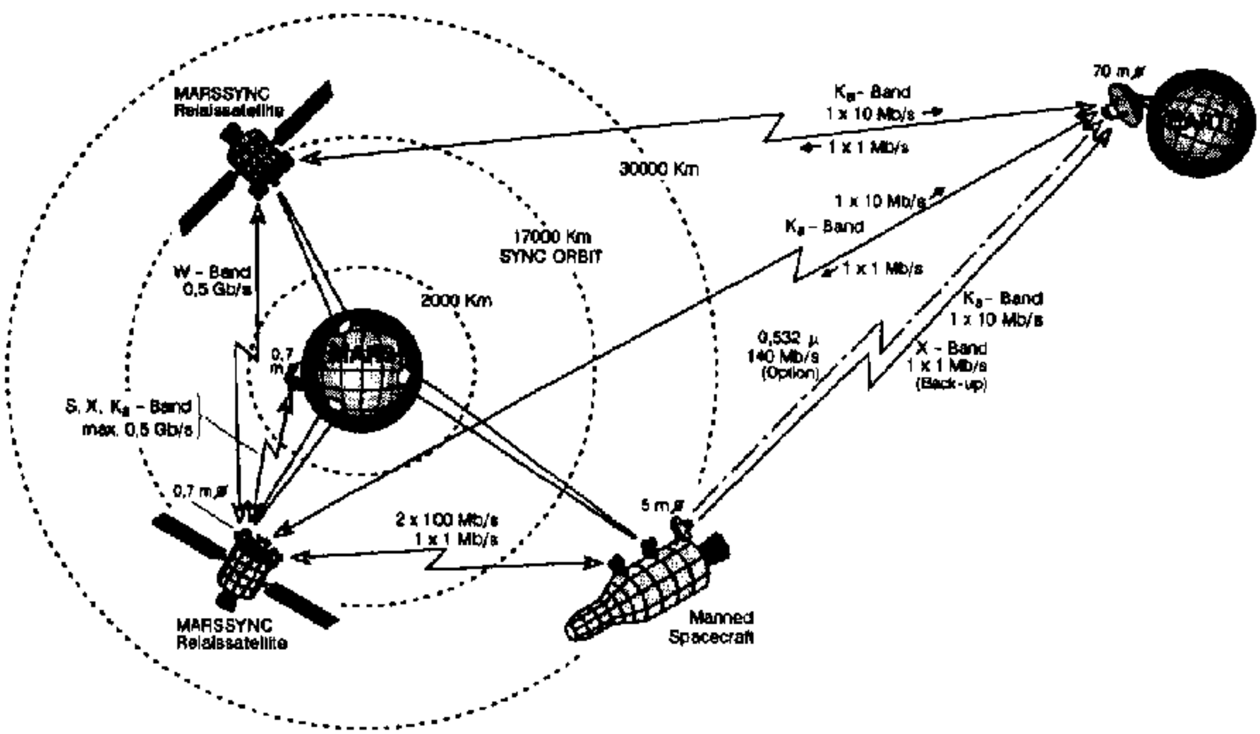

Fig. 7: Mars Communication Concept

The Mars Communication Concept aims for an optional 140 Mb/s optical telemetry link at a wavelength of 0.532 µm. The Mars orbiter will feed 12W into a 0.5 m diameter telescope, the Mars ground station under study will generate 6W into 1 m telescope (Fig. 7).

The earth ground station will use a 10 m-Telescope and a heterodyne receiver /4/. A link estimate is added in Tab. 1.

5. Drawbacks and Problems of Realization

Unfortunately, the small beamwidth as the main advantage of optical space communication systems is also responsible for the main disadvantage. The very small beamwidth complicates acquisition and tracking. Therefore, in addition to the optical communication packet, high accuracy and high speed pointing, acquisition and tracking subsystems (PAT) are required to reduce the influence of satellite vibrations to avoid a total optical link break. The main problem of realizing the communication subsystem is based on the nonexistent optical components for the low optical wavelengths desired in space. Whereas in optical fiber communication systems higher wavelengths are preferred (e.g.: 1500 nm), optical space systems prefer lower wavelengths (e.g.; 532 nm; visible). Note, that the fiber attenuation loss (due to material effects) decreases with higher wavelengths, whereas the free space beam spread loss (due to geometrical effects) decreases with lower wavelengths. Today, most available commercial optical components, as optical phase modulators, optical isolators and copplers are available for wavelengths, which are typical for optical fiber applications, as 850 nm, 1300 nm or 1500 nm. Against that, nearly no optical components are available for the Nd: YAG laser wavelength of 1.064 respectively 0.532 (doubled frequency) µm (except high-cost single fabricates) at this time.

The doppler frequency as a result of the relative motion of two linked satellites is another problem in realizing a coherent optical space communication system. Considering an optical LEO-GEO link, the maximum doppler frequency shift is in the order of 10 GHz. During one earth circulation of LEO the intermediate frequency (IF) of the heterodyne receiver changes from f_{IF} + 10 GHz to f_{IF} - 10 GHz, where f_{IF} denotes the average IF. To solve this problem, the coherent optical receiver must include a tunable local laser with a tunable frequency span of 20 GHz and a powerful automatice frequency control (AFC). In fiber optics, doppler effects are non existent.

6. Experimental Coherent Optical System Set-up at DLR

At DLR’s Institute for Communications Technologies an experimental 565 Mb/s optical DPSK system including a high power solid-state transmitter laser and an optical heterodyne receiver is under test.

The diode pumped Nd: YAG single mode laser with a present output of 600 mW (development goal: 1 W) provides a linewidth less than 100 KHz, thus allowing coherent modulation schemes as DPSK and PSK.

The high power laser is locked to a low power solid state monolithic Nd: YAG ring laser, which is commercially available. A pigtailed $LiNbO_3$ travelling wave modulator is used for phase modulation.

The frontend of the receiver includes 2 balanced InGaAS PIN photodiodes and a transimpedance amplifier (average power density 14 pA/√Hz). A ring laser is used as LO.

The IF of 1130 MHz is AFC-stabilized by a thermoelectric heater and a piezo element to control the local laser frequency. The IF filter bandwidth is 1000 MHz. A double balanced ring mixer is used as DPSK demodulator. The baseband signal is filtered by a 325 MHz 10-pole Bessel low-pass filter.

7. Acknowledgments

I feel obliged to thank Professor H.J. Becker from the Fachhochschule Düsseldorf for his critical review and comments to various deep space link calculations.

Further to Mr. F.L. Porsch for his outstanding assistance in designing the illustrations of this paper.

8. References

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[illegible]	
Laser Pulse Energy	$P \cdot \tau = N \cdot h \cdot f$
Photons transmitted	$N = \frac{P \cdot \tau \cdot \lambda}{h \cdot c}$
Laser beamwidth (const. illum. cone)	$\theta = 2 \cdot \frac{\lambda}{d_L}$
Photons received in a distance R	$n = \frac{N}{\frac{\pi \cdot R^2}{4} \cdot \theta^2} \cdot \frac{\pi \cdot d_R^2}{4}$
$n = \frac{1}{4 \cdot h \cdot c} \cdot \frac{P \cdot \tau \cdot d_L^2}{\lambda} \cdot \frac{1}{R^2} \cdot d_R^2$ (constant, laser, distance, receiver aperture)	

[illegible]	
n ≈ 8.9 Photons / Pulse	$P = 6$ [W] $\tau = 10^{-9}$ [s] $\lambda = 0.532$ [µm] $h = 6.62 \cdot 10^{-34}$ [Js] Planck's Constant $d_L = 1$ [m] $d_R = 10$ [m] $R_{max} = 4 \cdot 10^{8}$ [km]
bits / photon $\frac{256}{8.9 \cdot 8} = 3.6$ for 8-PPM (256 b) mod. scheme, no system losses considered.	
JPL has demonstrated 2.5 b / photon in Lab /2/	

Tab. 1 : Interplanetary Laser Communication Link