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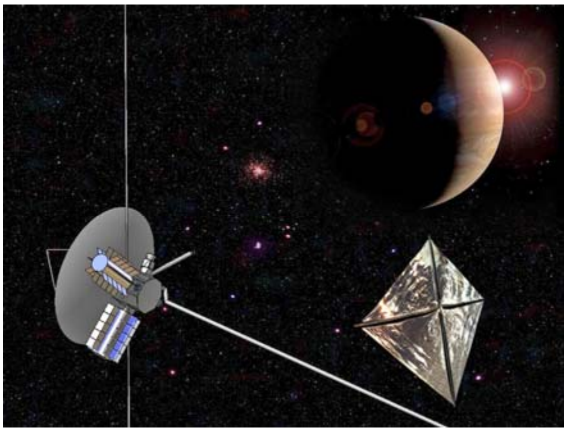
Interstellar Heliopause Probe Technology Reference Study

COMMUNICATION AT LARGE DISTANCES



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1 INTRODUCTION

The Interstellar Heliopause Probe is one of ESA's technical reference studies (TRS, see also http://sci.esa.int/concepts). The goal of the TRSs is to focus on the development of strategically important technologies that are of likely relevance for future scientific missions. This is accomplished through the study of several technologically demanding and scientifically interesting missions, which are currently not part of the ESA science programme. The TRSs subsequently act as a reference for possible future technology development activities.

The mission objective of the Interstellar Heliopause Probe TRS is to explore and investigate the interface between the local interstellar medium and the heliosphere. It will perform in-situ measurements of the particles and magnetic field in the interstellar medium and outer heliosphere at distances larger than 100 AU from the sun.

Low power deep space communication technology is an enabling technology for the Interstellar Heliopause Probe Technology Reference Study. Radio wave communication capable of performing this task exists today, but they are heavy and require significant electrical power. Optical communication technology on the other hand is still immature.

This short document summarizes the results of a communication subsystem trade performed by Kayser-Threde, as part of the Interstellar Heliopause Probe system design study [Leipold05, Leipold06]. The objective was to identify and investigate optical and radio wave deep space communication systems capable of delivering the required performance of the Interstellar Heliopause Probe TRS.

For deep space communication systems at distances below ~20 AU, the reader is referred to the Jovian Studies Overview (http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=40866#), and the Venus Entry Probe Technology Reference Study overview (available from http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=40093).

2 COMMUNICATION REQUIREMENTS

Long distance communication at distances of 200 AU from Earth will be a substantial technological challenge. This is about twice the distance of the furthest scientific probes today (Voyager 1 passed 100 AU in august 2006, and will reach ~148 AU in 2020).

The requirements assumed for the TM/TC system for the IHP TRS are:

- A downlink data rate of 200 bps at 200 AU (1000 bps for early mission phases)
- An uplink data rate of 5 bps

The following subsystem requirements were defined during the study phase:

- The subsystem mass shall be less than 35 kg

- The subsystem average power shall less than 35 W
- The antenna size shall be compatible with payload FOV requirements (maximum diameter 1.5 m)
- The imposed S/C pointing accuracy shall not be better than ~0.5°
- Cold redundancy for uplink and downlink

3 RADIOWAVE VS OPTICAL COMMUNICATION

Traditionally microwave has been the communication form of choice for most missions, as it is has a large heritage and its characteristics are well known. However, it does have certain limitations. This section will discuss the key differences between radiowave and optical communication systems.

3.1 Microwave communication

The following frequency bands have been considered for the frequency trade-off for the IHP TRS:

- X-band: conventional high-gain antenna
- Ku-band: conventional high-gain antenna
- Ka-band: conventional high-gain antenna

Table 3-1 shows the standard definition of RF frequency ranges considered.

Band	**Wavelength [cm]**	**Frequency [GHz]**
X	***3.75 - 2.4***	***8 - 12***
Ku	***2.5 - 1.6***	***12 - 19***
Ka	***1.6 - 0.75***	***19 - 40***

Table 3-1: Frequency table.

X-band and Ka-band communication systems are conventionally used for deep space communication systems. A ground station infrastructure exists to support these communication frequencies.

3.2 Optical communication

Optical communication in space has been successfully demonstrated with the SILEX experiments on SPOT-4 and Artemis (see http://www.esa.int/esaCP/ESASGBZ84UC_index_0.html), and more recently with the Japanese Optical Inter-orbit Communications Engineering Satellite (http://www.jaxa.jp/projects/sat/oicets/index_e.html) and the Laser Link experiment on SMART-1 (http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31415&fbodylongid=862).

The technology might be used in the future for deep space applications as well. The key aspects of optical communication are:

- Optical communication uses an extremely narrowly focused laser beam (~ arc seconds) to transmit information. This requires a very accurate pointing and tracking accuracy on the spacecraft, more than can be achieved with the best star trackers. Current optical communication strategies use a wide laser beacon (on Earth or spacecraft) for the spacecraft to lock-on to. However, at far distances (> 1 AU), this requires a very powerful laser, or a sophisticated spacecraft pointing strategy, using e.g. the sun or the sun-illuminated Earth (see e.g. [Lee01, Ortiz03]).
- In theory, the signal to noise ratio of optical communication is better than Ka band by a factor of 10 000 000 (70 dB). Background noise, atmospheric attenuation, clouds etc. reduce this figure.
- The transmitting station needs to be a refractive telescope; receiving station may be only a photon collector (cheaper solution, only counts photons).
- The effective transmitted power can be increased by modulation of the light pulses (average power stays the same).

Current and future optical communication systems:

- Artemis and SPOT-4 are still in orbit. The optical communication system on Artemis weighs 90 kg, similar system today would weigh about 30 kg.
- SMART-1 has conducted a deep-space laser-link tracking experiment using an on-board camera and a laser beam from the ESA Optical Ground Station.
- TerraSAR-X, a German X-band radar satellite, contains an experimental payload package to provide an optical bidirectional communication link between a second satellite or with optical ground station. It is scheduled for launch in May 2007. (See wwwserv2.go.t-systems-sfr.com/tsx/start_en.htm and http://directory.eoportal.org/pres_TerraSARXMission.html)
- Four optical communication ground stations exist (Optical Ground Station Oberpfaffenhofen/Germany/DLR, Table Mountain Facility/California/JPL, ESA-OGS/Tenerife/ESA, CRL-OGS/Tokyo/).

The advantages compared to radio-wave communication are clearly the relatively high data rates achievable with modest power and antenna sizes. Existing ground telescopes (10 meter class) could be used for downlink, though for continuous use a dedicated ground station, with uplink capabilities, will likely be required. The main disadvantages are the high pointing accuracy requirement for the laser beam (order of arcseconds) as well as the lifetime of semi-conductor lasers. Also cloud coverage is a significant concern for optical communication, as no link to an Earth ground station is possible if clouds exist. Hence, more than one ground station is necessary in order to get a high downlink and command up-link probability.

For further reading, please see [Toyoshima05] and references therein.

3.3 Trade-off summary

Table 3-2 compares the different options. Color coding has been used for ranking: Green marks a good performance, yellow is average performance. For the trade-off, a S/C High Gain Antenna (HGA) beam width of 1.6° has been assumed. All mass estimates are for single string configuration (no redundancy).

	X-Band	**Ku-Band**	**Ka-Band**	**Optical (Laser)**
Wavelength/Frequency	~ 8 GHz	~ 15 GHz	~ 30 GHz	~ 1064 nm
Frequency assignment	possible	possible	good	not regulated
Possible bandwidth	medium	medium	medium	extremely high
S/C pointing requirement	≤ 0.5°	≤ 0.5°	≤ 0.5°	≤ 0.1°
Beam pointing requirement	~0.5°	~0.5°	~0.5°	~0.0001°
Data rate @ 200 AU	~ 200 bps	~ 200 bps	~ 200 bps	~ 1000 bps
Link budget	OK	OK	OK	OK
Atmospheric effects	small effects	noticeable	significant, depends on altitude of GS	can be severe, depends on e.g. clouds
Minimum elevation above the ground station horizon	4°	5°	9°	10°
Receiver noise level	low	acceptable	significant	acceptable
S/C antenna size	Ø 3.6 m	Ø 1.5 m	Ø 1.25 m	Ø 0.6 m
Ground antenna size	≥ 30 m	≥ 20 m	≥ 17.5 m	≥ 1.5 m
Low distance operation < 5 AU	separate LGA	separate LGA	separate LGA	experimental stations existing
Ground station	existing	not existing	existing	dedicated required
Operation at 5-50 AU	beam spreading	beam spreading	beam spreading	bigger sensor array
EMC interference	~ 20 mV / m	~ 20 mV / m	~ 6 mV / m	none
Subsystem mass incl. antenna	20 kg	12 kg	10 kg	22 kg
Power consumption	34 W	34 W	38 W	35 W
Lifetime	good	good	good	limited by laser semiconductors
Redundancy	possible	possible	possible	complex
TRL	7: Established technology, but miniaturization required	7: Established technology, but miniaturization required	7: Established technology, but miniaturization required	5: Few sensitive detector systems available

Table 3-2: Trade-off for X-, Ku-, Ka-band and optical communication.

As the baseline for the IHP TRS, the Ka-band solution has been selected because it provides adequate performance and has an acceptable TRL, while requiring the least mass.

4 COMMUNICATION SUBSYSTEM FOR IHP

Figure 4-1 shows a functional block diagram of the baselined communication subsystem for the IHP TRS. The block diagram shows only one of five low gain antennas distributed over the spacecraft bus to achieve omni-directional coverage.

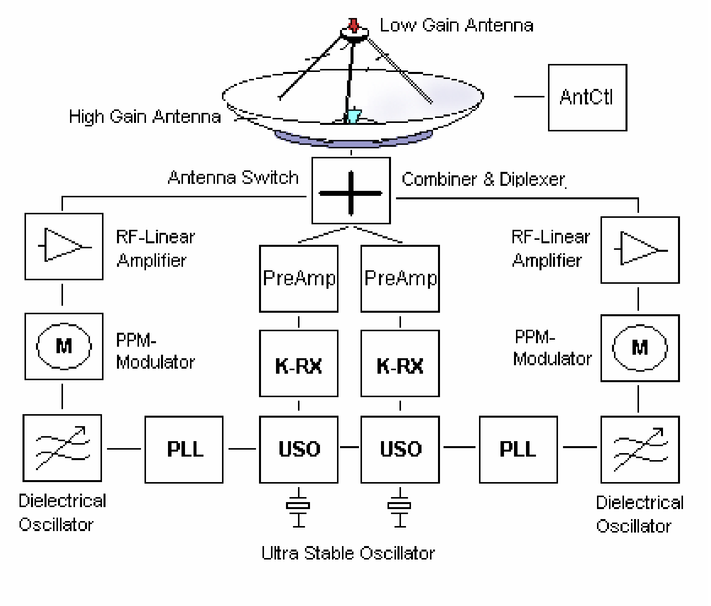

Figure 4-1: IHP TM/TC subsystem block diagram

At distances below 5 AU, during the solar sailing phase, a set of 5 Low Gain Antennas (LGAs) is used to achieve omni-directional coverage. For medium distance communication (5-50 AU), a piezo-controlled defocusing mechanism is used to widen the antenna beam of the High Gain Antenna (HGA) to about 15°. At longer distances the HGA is always pointed towards the Sun and thus also directed towards the Earth. An antenna steering mechanism ensures that the Earth orbit is within the antenna beam width of 1.6°.

In order to limit the RF power requirements, the communication link is based on Impulse Radio: The signal is transmitted as carrier-free short duration pulses (< µs) that are time-synchronized by an on-board ultra-stable oscillator. The very low duty cycle (on the order 1/100, 1/1000 or less) reduces the input power and concentrates all the RF power on a single impulse. Information is transmitted by On/Off Keying (Pulse-Position Modulation).

The total mass for a dual-redundant communication subsystem is 20 kg (including subsystem margin). The nominal power when transmitting is 34 W.

5 REQUIRED TECHNOLOGY DEVELOPMENTS

This RF communication design requires several new component technologies, especially the high power transmitter RF pulse technology. The following RF communication components are not available in space quality at the moment:

1) Power supply technologies for supporting of high power loads during short impulses (e.g. high capacitive capacitors) (TRL = 3)
2) RF semiconductors for RF power about 2 kW at Ka band (TRL = 2)
3) High stable oscillators based on sapphire technology instead of classical crystal oscillators (TRL = 4)
4) New narrow band design strategies and technologies for low noise receivers at Ka band (TRL = 2)
5) Space qualified signal processing inside the demodulator detectors (digital signal processors) (TRL = 2)
6) Steerable high gain antenna (for beam steering and defocusing) (TRL = 3)

In addition to the on-board equipment, the IHP ground segment needs to be upgraded to be capable to operate with the Impulse Radio scheme at Ka-band. Though several ESA ground stations will likely be upgraded in frame of other programs to Ka-band, Impulse Radio modulation is not foreseen.

6 CONCLUSION

For the IHP TRS, an RF communication system has been baselined. Though the concept of deep space optical communication is promising, several important technological challenges would need to be solved first.

The TM/TC RF subsystem design for the IHP TRS is highly innovative through the use of PPM modulation technology together with the high-precision on-board time information using an ultra-stable oscillator. This approach allows the realization of a low-resource spacecraft to communicate at very large distances, as the HGA size, the TM/TC equipment mass as well as the necessary on-board power are minimal.

7 REFERENCES

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8 ACRONYMS

AU	Astronomical Unit (1.496 × 10^8 km)
EMC	Electro Magnetic Compatibility
ESA	European Space Agency
HGA	High Gain Antenna
IHP	Interstellar Heliopause Probe
LGA	Low Gain Antenna
RF	Radio Frequency
S/C	Spacecraft
SCI-A	Science Payload & Advanced Concepts Office
TM/TC	Telemetry/Telecommand
TRS	Technology Reference Study