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Reverse Engineering of Juno Mission

Homework 3

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Group 5

Alex Cristian Turcu	alexcristian.turcu@mail.polimi.it	10711624
Chiara Poli	chiara3.poli@mail.polimi.it	10731504
Daniele Paternoster	daniele.paternoster@mail.polimi.it	10836125
Marcello Pareschi	marcello.pareschi@mail.polimi.it	10723712
Paolo Vanelli	paolo.vanelli@mail.polimi.it	10730510
Riccardo Vidari	riccardo.vidari@mail.polimi.it	10711828

Contents

Notation

TMTC	Telemetry and Telecommand
HGA	High Gain Antenna
MGA	Medium Gain Antenna
LGA	Low Gain Antenna
TLGA	Toroidal Low Gain Antenna
TWTA	Traveling Wave Tube Amplifier
ALGA	Aft Low Gain Antenna
FLGA	Forward Low Gain Antenna
DSN	Deep Space Network
DSM	Deep Space Manuevers
JOI	Jupiter Orbit Insertion
PRM	Period Reduction Manuever
SDST	Small Deep Space Transponder
SSPA	Solid State Power Amplifier
DPM	Digital Processing Module
F1	Fundamental frequency
DOR	Differential One-way Ranging
RHCP	Right-Hand Circular Polarization
LHCP	Left-Hand Circular Polarization
RF	Radio Frequency
OTM	Orbit Trim Manuever
BPSK	Binary Phase Shifting Keying
MFSK	Multiple Frequency Shift Keying
AWVR	Advanced Water Vapor Radiometer
LNA	Low Noise Amplifier
KaTS	Ka-band Translator
IF	Intermediate Frequency
RF	Radio Frequency
RS	Radio Science
SR	Science Receiver
OLR	Open Loop Receivers
VLBI	Very Long Baseline Interferometry
BVR	Block-V Receivers
FTS	Frequency and Timing Subsystem
BER	Bit Error Rate
MWR	Micro Wave Radiometer
DSS	Deep Space Station
RSR	Radio Science Receiver
D/L	Downlink
U/L	Uplink
P_{rx}	Power received [W]
P_{tx}	Power transmitter [W]
G_{rx}	Gain receiver [-]
G_{tx}	Gain transmitter [-]
L_c	Cable losses [-]
L_s	Space losses [-]
$L_{p,tx}$	Receiver pointing losses [-]
$L_{p,rx}$	Transmitter pointing losses [-]
L_a	Atmospheric losses [-]
L_{cv}	Antenna cover losses [-]
k	Boltzmann constant [J/K]
T_{eq}	Equivalent temperature [K]
R	Datarate [bps]
N_0	Noise spectral density [W/Hz]
E_b	Energy per bit [J/bit]
r_{JE}	Juno-Earth distance [AU]
f	Frequency [Hz]
d_g	Ground antenna diameter [m]
η	Pointing error [-]
G	Antenna gain [dB]
θ_{bw}	Antenna beamwidth [deg]
$EIRP$	Equivalent isotropic radiated power [dBm]
$(.)_{mar}$	Margin value

1 TMTC system architecture

The Juno TMTC subsystem purpose is to communicate data about the status of the spacecraft, to send scientific data and to receive commands, from and to the DSN antennas. Both the uplink and downlink are performed in X-band frequency: 8.4 GHz for downlink and 7.1 GHz for uplink. The selection of this band was imposed by pre-existing DSN facilities. It allows to transmit relatively large datarates over wide distances with low atmospheric attenuation. One of the main goals of the mission is to study Jupiter's gravity field: this is accomplished by exploiting the difference in Doppler effect of the telecommunication from the model and the real jovian gravity field. Due to the harsh environment that Juno faces and the need to measure precisely the residual frequency, transmission on both X-band and Ka-band during gravity science is needed. The Ka-band has an advantage on the X-band since the noise due to interplanetary plasma is inversely proportional to the wavelength, higher on the Ka-band, making the measurements more accurate[1]. For this reason, the HGA can operate in 3 different modes:

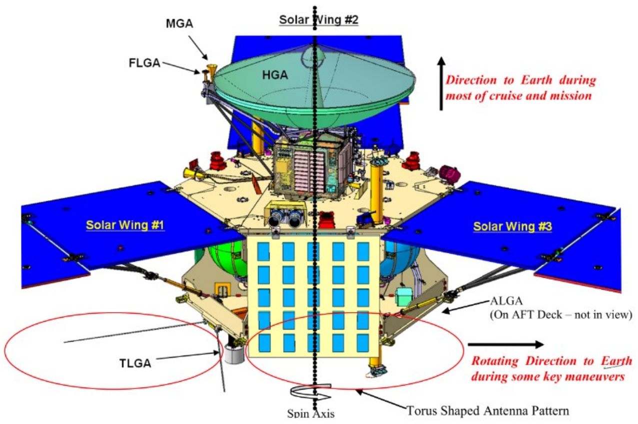

Figure 1: Location of telecommunication antennas

- **X/X**: uplink and downlink are coherent and performed in X-band;
- **X/X & X/Ka**: simultaneous transmission on X-band (uplink and downlink), together with a coherent Ka-band downlink at 32 GHz and X-band uplink;
- **X/X & Ka/Ka**: phase coherent X-band uplink and downlink together with a phase coherent Ka-band uplink at 34 GHz and downlink.

In order to calibrate the dispersive noise contribution when receiving X-band and Ka-band signals simultaneously, Juno is equipped with a KaTS. This instrument is capable of receiving a Ka-band uplink unmodulated carrier from DSN and to generate a Ka-band downlink unmodulated carrier coherent with the uplink to maintain the phase stability from ground communication, on which the quality of the experiments depends[2].
Five antennas are mounted on-board Juno with different orientations, positions and capabilities: one HGA, one MGA, two LGAs and one TLGA.
In order to process different signals at different frequencies, Juno has two SDSTs, capable of performing different tasks. The prime unit provides X/X and X/Ka link, whereas the secondary unit only operates on the single X-band. Each SDST is composed of four different units: the DPM, the down converter, the power converter and the exciter unit. The DPM is responsible for managing the data incoming from the down-converter, encoding them and providing X-band baseband telemetry. The down-converter module converts the incoming 7.1 GHz signal into an intermediate frequency at 4/3 F1, where F1, approximately 9.55 MHz, is the fundamental frequency from which up and downlink frequencies are derived. The power converter is responsible for supplying a steady voltage to all SDST modules and the exciter is responsible for taking as an input telemetry, DOR, ranging and for phase-modulating the downlink carrier[1][2].
The SDST is responsible for generating the X-band downlink carrier by coherently multiplying the frequency of the uplink carrier by a turn-around ratio of 880/749. All X-band signals are amplified by one of two-redundant 25 W TWTAs[2]. This kind of technology was imposed by the high power demand for the link on this frequency. For the Ka-band transmission, SSPA was preferred due to less required power for transmission and weight saving.
Before the transmission of the signal actuated by the antennas, the data is manipulated with modulation and encoding techniques. The chosen modulation is BPSK which ensures a good use of spectrum and relatively low BER. Moreover, it was flight-proven and requires less complex on-board architecture. Encoding is performed in two ways depending on the type of the transmission: the Reed-Solomon algorithm allowed lower BER to be reached, while Turbo code 1/6 was used for larger datarates of transmission.

1.1 HGA

The HGA[2][3] is the principal means of communication with Earth throughout most of the cruise and science mission. It is mounted on the forward deck, aligned with the spin axis of the spacecraft, as shown in Figure 1. Due to the significant distance between Juno and DSN antennas and the limited transmitter power, HGA gain maximization was a priority. Constraints on dish dimension and in the attitude control of the spin-stabilized spacecraft were present: the Atlas V fairing limited the HGA dish diameter to 2.5 meters, then the presence of massive solar arrays prevented pointing the main beam to anything tighter than about ± 0.25°. The latter limitation would have led to an insufficient gain in the HGA, preventing closing the link with Earth. The most limiting factor in designing

the HGA was the need of both transmitting and receiving on X-band and Ka-band without affecting excessively the performance of any signal. Because of these requirements, a dual-reflector Gregorian-style optics was installed. The latter consists in a parabolic main reflector and an elliptical sub-reflector, making the whole system low in mass and compact[3]. The outer annular region is made so that the radiated field of the X-band is 180° out of phase with the inner region aperture field: the resulted beamwidth of the Ka-band is approximately the same as the X-band one. This modification created almost no performance degradation on X-band link. Based on frequency and operational mode, different polarizations are utilized: X-band uses RHCP for both uplink and downlink, while Ka-band uses RHCP for downlink and LHCP for uplink[2]. Required gain is about 44 dB for the X-band in both uplink and downlink and around 47 dB for the Ka-band.
Other limiting factors were present in designing the HGA in terms of thermal and structural constraints: the stability in pointing at low temperatures is granted by a very stiff graphite composite. Moreover, the HGA's shielding from the high temperature oscillation (from -175°C to 135°C) and radiation dose experienced during both cruise and jovian phase is accomplished using a thermal blanket made of a carbon-loaded Germanium-Kapton material[3][4]. As a result, the performances were only affected by a loss of 0.25 dB at X-band and a 0.5 dB loss on the Ka-band.

1.2 MGA & LGAs

One MGA and two LGAs are mounted on-board Juno. Their position can be seen in Figure 1. Both types of antennas come as legacy from previous missions. LGAs were previously used on the Mars Reconnaissance Orbiter and as part of a family of antennas used for deep space missions. Instead, MGA was used in Mars Exploration Rover cruise stage[3].
The MGA is a conical horn-style antenna and it is aligned with the +Z-axis as the HGA and it is used during cruise, safe mode and manoeuvres. It is capable of both LHCP and RHCP for redundancy and communicates with the DSN only in X-band, using the same frequencies of the HGA. This antenna provides at least 18.1 dBic while receiving and 18.8 dBic while transmitting, with a 3 dB beamwidth of ± 10.3° and ± 9.3° respectively.
The two identical and coupled LGAs are pointing in opposite directions, one mounted on the forward deck (FLGA) and the other on the aft deck (ALGA). LGAs have a choked horn design and transmit on the same X-band frequencies as the MGA and HGA. While delivering inferior performances regarding the minimum required boresight (8.7 dB in receiving and 7.7 dB in transmitting), they operate with a higher 3 dB beamwidth at around ± 40°[2].
The LGAs are used mainly at a distance inferior to 0.5 AU from Earth and during manoeuvres, when orientation of the spacecraft does not allow HGA communications due to sun-pointing requirement. Throughout main engine burns, the MGA is used in sequence with HGA and TLGA. This suit of antennas is also used during MWR science configuration.

1.3 TLGA

The TLGA is placed on the aft deck of Juno, aligned with solar wing #1. This antenna works at the same X-band frequency of the other antennas but differs from them since it has a bi-conical horn design and it is able to produce a RHCP radial pattern around Juno's spin axis: this characteristic is needed to ensure continuous coverage during all critical events, such as the DSMs, JOI, PRM and OTMs, when the attitude does not allow for direct Earth pointing. This antenna transmits only in a carrier or subcarrier configuration, where no ranging nor telemetry signals are modulated onto the carrier. During ME manoeuvres Juno encodes MFSK tones by modulating a varying frequency subcarrier onto the carrier. Every subcarrier frequency is associated to a particular event or state of the spacecraft and allows a complete knowledge of Juno's health. The particular advantage of using a subcarrier is the capability of providing an additional channel of transmission: it allows different signals to be received together as one and then to be separated out by the receiver.
A toroidal antenna pattern can be produced by a dipole, but this design limits heavily the maximum gain reachable to around 2.2 dB, which is insufficient to provide communications between Juno and Earth. Thus, a bi-conical parabolic-shaped antenna with corrugated horn has been developed, allowing for a compact and efficient design: this configuration achieves values lower than 20 dB in return losses over the entire used X-band[3]. The RHCP pattern is achieved through a four-layer meander-line polarizer, built to minimize RF losses. As the HGA described in subsection 1.1, the TLGA is also covered in a Germanium-Kapton blanket to minimize high energy electrons' flux. Gains required for the TLGA are of 5.5 dBic while receiving and 6.5 dBic while transmitting, with a beamwidth of ± 10° in both reception and transmission at ± 90° with respect to the boresight angle[2].

1.4 Ground stations

In order to retrieve data, Juno relies on the antennas of NASA's DSN, a system of three complexes spread around the globe, separated by approximately 120° in longitude: one is located in Goldstone, California; one in Madrid, Spain; the last one in Canberra, Australia. This configuration allows for constant observation of spacecraft while Earth rotates, as can be visualized in Figure 2. Each site is fitted with one 70-meter diameter antenna and a set of 34-meter diameter antennas. At Ka-band, the beamwidth of the latter antennas is 4 times narrower than the X-band beamwidth (0.016° vs. 0.077° respectively), making the pointing critical to establish a stable link with the spacecraft.

All antennas are capable of receiving and transmitting in X-band, however only the smaller ones are also capable of receiving in Ka-band. DSS-25 antenna in Goldstone is the sole capable of Ka-band uplink: all Juno's closest approach periods to Jupiter are planned such that this particular antenna is in sight.
Since the troposphere introduces delays in the Doppler signal path, in order to retrieve a more accurate reading during gravity science, DSS-25 is equipped with a AWVR that measures the wet component of the troposphere and various frequencies, including 31.4 GHz, where Ka-band signal are performed. The wet component delays are statistically combined with data considering effects from surface meteorology to have a full evaluation of the delays in the Doppler signals[5].
During communications, the signal is received by the antennas and then amplified by the LNA into an IF (at 300 MHz) easier to be carried by cables rather than a RF, that needs waveguides. Depending on the flexibility needed, an open-loop or closed-loop or monopulse closed-loop can be used for signal processing. There have been three types of open-loop receivers during Juno era, all functioning in similar capacities: RSR, VLBI, WVSR. The last two have been recently replaced by a more recent OLR due to obsolescence issues in maintenance[6]. Open-loop receivers opt for a specific band of frequencies to amplify and then transmit the data to RS or VLBI equipment for processing and storage. They are used during high-dynamic or low-signal level events because of their ability to best guess the frequency of the received signal in order to sample the entire spectrum around the spacecraft's center frequency. Regarding closed-loop receivers, they are based on the advanced technology of BVRs, in which the spacecraft's downlink is selected and received. BVRs are able to detect subcarriers carrying telemetry or ranging data and to decode and process them. A program known as *conscan*[7] is in charge of observing the strength of the receiver's signal to optimize the antenna's pointing via small circular movements. The usage of *conscan* during VLBI or RS operations is discouraged due to variations in signal levels, in its place a monopulse closed-loop receiver is used to optimize Ka-band reception. The monopulse system compares the gain and the phase of the received Ka-band signal to estimate needed corrections in the antenna's pointing to improve signal-to-noise ratio by 1÷3 dB-Hz[1].

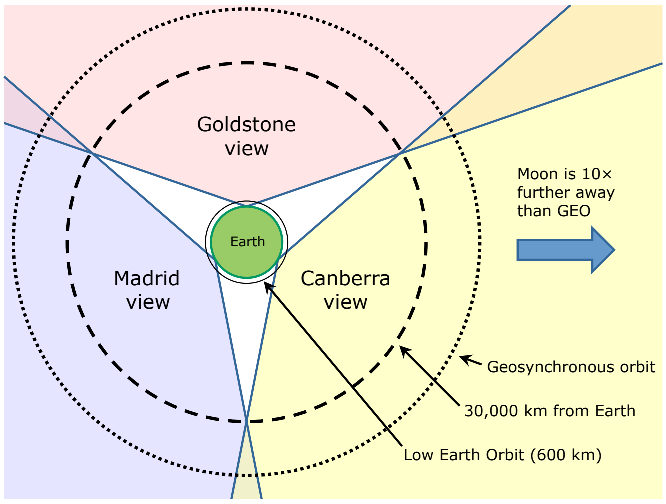

Figure 2: DSN coverage

X-band and Ka-band signals are generated by the FTS, which relies on a hydrogen maser clock to maintain a stable reference frequency. The X-band exciter and Ka-band exciter generate an uplink carrier signal which is amplified by the transmitters. The Juno spacecraft then receives these signals and phase-coherently retransmits them to the DSN antenna. In Figure 3 it is possible to observe a simplified scheme of Juno's communication architecture.

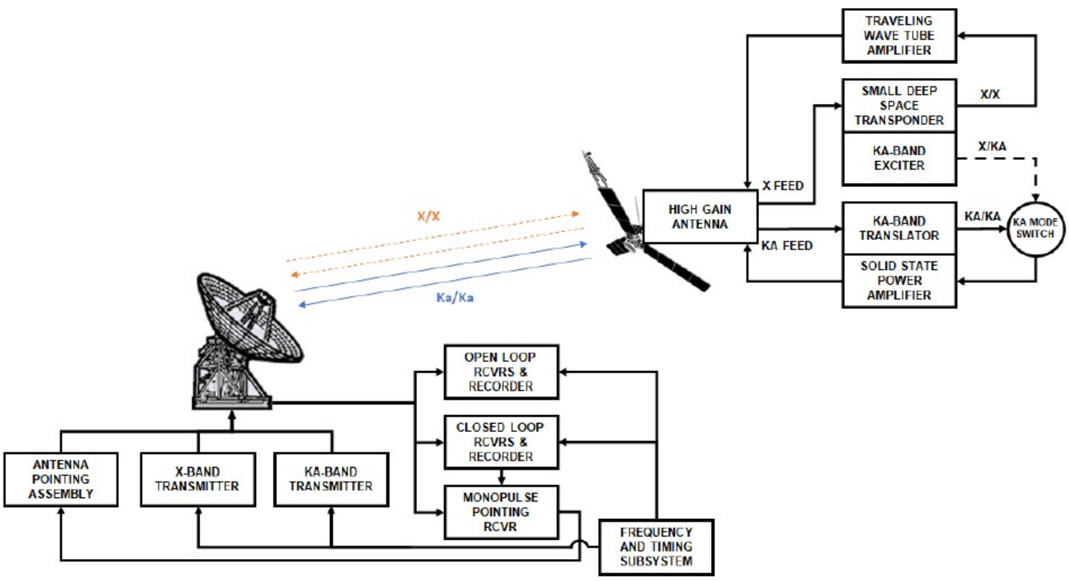

Figure 3: Ground Station and Juno communication scheme

2 Phases breakdown

The satellite utilizes all the antennas throughout the different phases of the mission. During each one, the TMTC system must satisfy different linking requirements. The main phases are depicted in time in Figure 4 and then briefly discussed in Table 1.

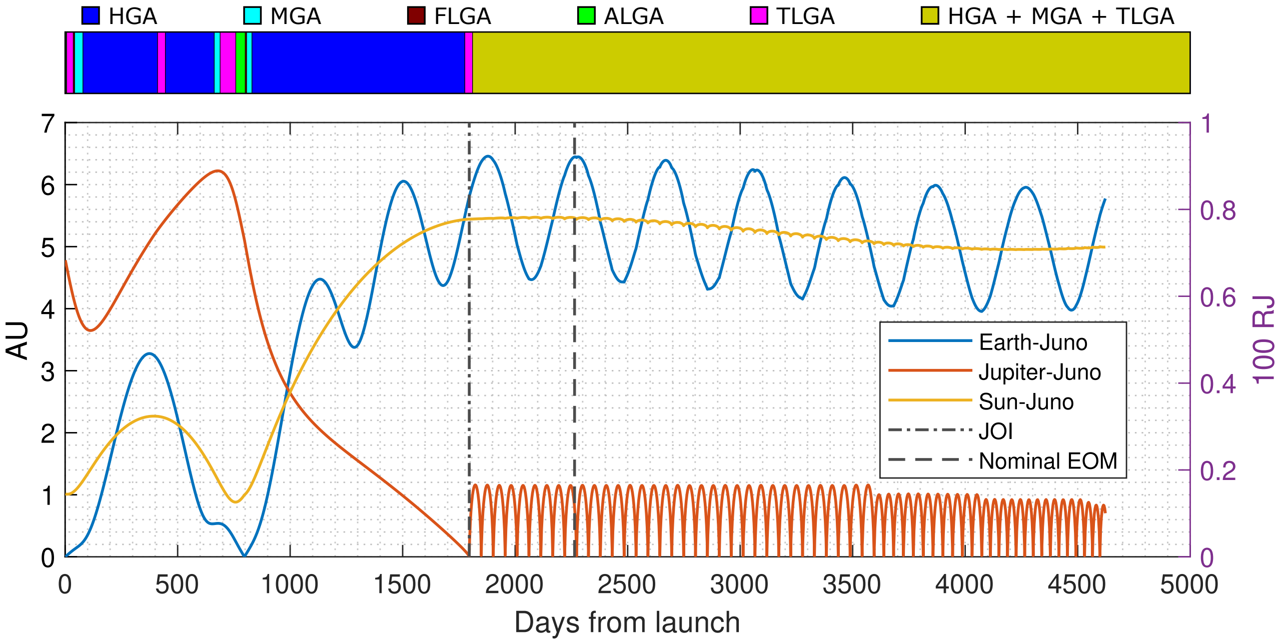

Figure 4: Antennas operability during mission

Phase	Downlink/Uplink [bps]	Phase summary
Initial Acquisition	1745 / -	Initial acquisition performed through LGAs (zoom on Figure 4). Reed-Solomon coding was used.
Cruise	100 / 7.8125	Ranging is on during the whole cruise. Since Juno has to point the Sun, HGA is not usable during fly-by so all the other antennas are sequentially employed (Figure 4).
Orbital Operations	$1.8 \cdot 10^4$ / 2000	This is the most demanding phase, it requires at least 18 kbps in downlink through HGA. Also MGA and TLGA are used during OTMs, the latter only for tones (Figure 4).
Critical Event Coverage	- / -	No data during these phases, just tones through TLGA.
Safe Mode	10÷40 / 7.8125	Downlink datarate may be changed by flight software. Ranging is switched off during this mode.

Table 1: Summary of data links during mission phases[2]

3 Reverse sizing of the HGA

The reverse sizing of the HGA is based on the link budget equation that represents a power balance between the transmitted signal and the receiver noise. The same equation can be applied on both uplink and downlink. It is valid for all the architectures, both that transmit data or tones.

$$\frac{P_{rx}}{N_0} = \frac{P_{tx} G_{tx} G_{rx} L_{tot}}{k T_{eq}} > \left(\frac{P_{rx}}{N_0}\right)_{min} \tag{1}$$

For antennas that broadcast data, an additional equation is used to constrain the sizing.

$$\frac{E_b}{N_0} = \frac{P_{tx} G_{tx} G_{rx} L_{tot}}{k T_{eq} R} > \left(\frac{E_b}{N_0}\right)_{min} \tag{2}$$

L_{tot} considers the following losses:

$$L_{tot} = L_c \cdot L_s \cdot L_{p,tx} \cdot L_{p,rx} \cdot L_a \cdot L_{cv} \tag{3}$$

For each communication link, different minimum required ratios are defined. In particular, $\frac{E_b}{N_0}$ must also satisfy the Shannon theorem by ensuring a value higher than −1.59 dB. The HGA, as described in subsection 1.1, is used for the downlink of telemetry and scientific data during the science orbits around Jupiter. It has been sized in the following scenario:

- the maximum distance from Earth $r_{JE} = 6.5$ AU;
- the minimum datarate $R = 18$ kbps has to be ensured regarding the distance.

From the literature, some other parameters were recovered and reported in Table 2. The results of the sizing are shown in Table 3. In particular, some margin is present on both X-band and Ka-band. Since the X-band is the only one transmitting data, Figure 5 and Figure 6 focus on the margin of the downlink. The principal loss of the link is given by the distance, so the two design parameters have been described as a function of it.

	X-D/L	X-U/L	Ka-D/L	Ka-U/L
f [GHz]	8.4	7.1	34.4	32.1
R [kbps]	18	2	–	–
d_{HGA} [m]	2.5			
d_g [m]	34			
P_{tx} [W]	25	$1.8 \cdot 10^4$	2.5	$1.8 \cdot 10^4$
η_{HGA} [deg]	0.25			
η_g [deg]	$4 \cdot 10^{-3}$		$2 \cdot 10^{-3}$	
L_c [dB]	−2	–	−2	–
L_a [dB]	−0.2		−1.09	
L_{cv} [dB]	−0.25		−0.5	
T_{eq} [K]	21	401.25	21	770.63
$\left(\frac{P}{N_0}\right)_{min}$ [dB-Hz]	43.64	49.13	26.50	42.57
$\left(\frac{E_b}{N_0}\right)_{min}$ [dB]	−0.1	9.6	–	–

Table 2: HGA data for sizing[2]

	X-D/L	X-U/L	Ka-D/L	Ka-U/L
G_{HGA} [dBi]	44.25	42.79	56.50	55.90
G_g [dBi]	66.93	65.47	79.17	78.57
$\theta_{bw,HGA}$ [deg]	0.932	1.10	0.438^{I}	
$\theta_{bw,g}$ [deg]	0.069	0.081	0.017	0.018
L_s [dB]	−290.63	−289.17	−302.88	−302.28
L_p [dB]	−0.904	−0.646	−4.09	−4.51
$EIRP$ [dBm]	85.98	138.02	87.98	151.12
N_0 [dBm/Hz]	−185.38	−172.57	−185.38	−169.73
P_{rx} [dBm]	−138.83	−109.46	−140.90	−101.36
$\frac{P}{N_0}$ [dB-Hz]	46.55	63.11	44.47	68.38
$\left(\frac{P}{N_0}\right)_{mar}$ [dB-Hz]	2.91	13.98	17.97	25.81
$\frac{E_b}{N_0}$ [dB]	4.00	30.10	–	–
$\left(\frac{E_b}{N_0}\right)_{mar}$ [dB]	4.10	20.50	–	–

Table 3: Results for HGA

^{I} This value was recovered from a graphical analysis of the HGA Ka-band gain pattern.[2]

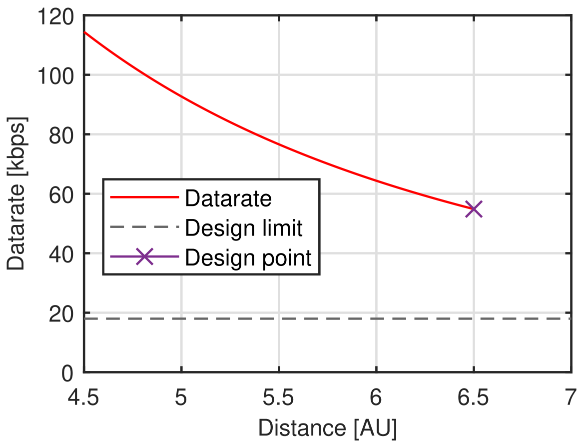

Figure 5: Datarate as function of distance by fixing E_b/N_0 = -0.1 dB

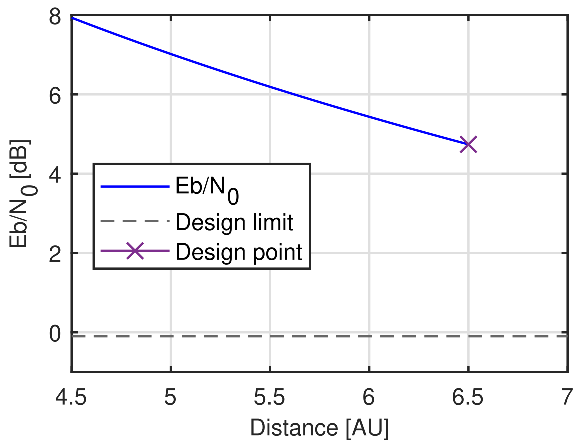

Figure 6: Energy per bit to noise ratio as function of distance by fixing R = 18 kbps

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