# Feasibility Study for a Reduced Planetary Navigation and Communication System

# PLANCOM

# Executive Summary

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# PROJECT OVERVIEW

In the near future, an increasing number of missions will explore the Solar System. Both the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) exploration programmes are focussing in Moon, Mars, and asteroids to gather scientific and engineering information, paving the way for permanent human establishments. The planned robotic and manned missions will demand navigation and communication services to support surface operations on these scenarios.

In this project, a reference local (planetary) infrastructure is defined covering all the different possibilities of future planetary missions. In particular, definition of a communication and navigation network using an integrated signal is presented, allowing the provision of in-situ services such as high-quality video, audio channels, data network, or biomedical data.

A common Orthogonal Frequency-Division Multiple Access (OFDMA) signal based on the IEEE 802.16 WiMAX standard has been specifically designed for the planetary links. The different services are multiplexed in the wideband signal. Navigation capabilities are provided integrated in this waveform, allowing relative real-time positioning in planetary surfaces. Specific algorithms for non-real time positioning using the available orbit relays are also considered.

A coverage analysis has been carried out, based on terrain topography and ray-tracing algorithms, in selected locations (three in Mars and one in the Moon). Transmitted signal parameters are configurable to fulfil data and bit error rate (BER) requirements, and to achieve the specified position accuracy, solution rate, and time-to-first fix figures.

In this document, the PLANCOM project activities are briefly described, including a scenario overview with the local infrastructure in Moon and Mars, a description of the proposed integrated waveform, the receiver architecture, the navigation approach, and the simulation environment. The software tools developed in the project, and the obtained results are also presented.

# SCENARIO DEFINITION

Table 1 shows the system elements of the considered scenario, including the required range, links, communication and navigation capabilities, and the expected crew inside them. Figure 1 shows an artistic view of the PLANCOM scenario to be considered in the project. Table 2 shows the communication and navigation links that must be set to allow a full interoperability between the different system elements.

| System Element | # | Range | Links | Com. | Navigation | Crew |
|---|---|---|---|---|---|---|
| **Surface Habitation Module (SHM)** | **1** | Short / Long | Surface-to-Surface<br>Surface-to-Orbit | Duplex | Short range: Signal Transmission<br>Long range: Initial position determination | 2-6 |
| **Communication Base Station (CBS)** | **2** | Short / Long | Surface-to-Surface<br>Surface-to-Orbit | Duplex | Short range: Signal Transmission<br>Long range: Initial position determination | Un-manned |
| **Repeaters** | **2** | Short / Long | Surface-to-Surface | Duplex | Initial position determination and re-transmission | Un-manned |
| **Planetary Exploration Vehicle (PEV)** | **2** | Short / Long | Surface-to-Surface | Duplex | Typical: relative real-time.<br>Extreme: non-real time absolute. | 1-2 |
| **Astronaut suit (EVA)** | **4** | Short | Surface-to-Surface | Duplex | Typical: relative real-time.<br>Extreme: non-real time absolute. | 1 |
| **Rover** | **4** | Short / Long | Surface-to-Surface<br>Surface-to-Orbit | Duplex | Typical: relative real-time.<br>Extreme: non-real time absolute. | Un-manned |
| **Microsensors Device** | **5** | Short | Surface-to-Surface | Half-Duplex | N/A | Un-manned |
| **Transfer Vehicle** | **1** | Long | Orbit-to-Orbit | Duplex | Long range | 2-6 |
| **Ascent/Descent Vehicles** | **1** | Long | Orbit-to-Orbit | Duplex | Long range | 2-6 |
| **Orbiters** | **3** | Long | Orbit-to-Surface<br>Orbit-to-Orbit | Duplex | Long range: transmission | Un-manned |

*Table 1: System elements*

| | SHM/CBS | Repeaters | PEV | Astronaut | Rovers | Microsensor | TV | PAV | Orbiter |
|---|---|---|---|---|---|---|---|---|---|
| **SHM/CBS** | Ss5 | Ss5 | Ss2 | Ss3 | Ss4 | Ss8 | So1 | | So3 |
| **Repeaters** | Ss5 | Ss5 | Ss2 | Ss3 | Ss4 | | | | |
| **PEV** | Ss2 | Ss2 | Ss1 | Ss6 | | | | | So2 |
| **Astronaut** | Ss3 | Ss3 | Ss6 | Ss7 | | | | | So2 |
| **Rovers** | Ss4 | Ss4 | | | | | | | So2 |
| **Microsensor** | Ss8 | | | | | | | | |
| **TV** | So1 | | | | | | | Oo2 | Oo1 |
| **PAV** | | | | | | | Oo2 | | Oo3 |
| **Orbiter** | So3 | | So2 | So2 | So2 | | Oo1 | Oo3 | Oo1 |

**Green**: short range (ground) **Grey**: short/long range (ground) **Blue**: long range (orbit)
**SS**: Surface-to-surface link **So**: Surface-to-orbit link **Oo**: Orbit-to-orbit

*Table 2: Communication/Navigation links*

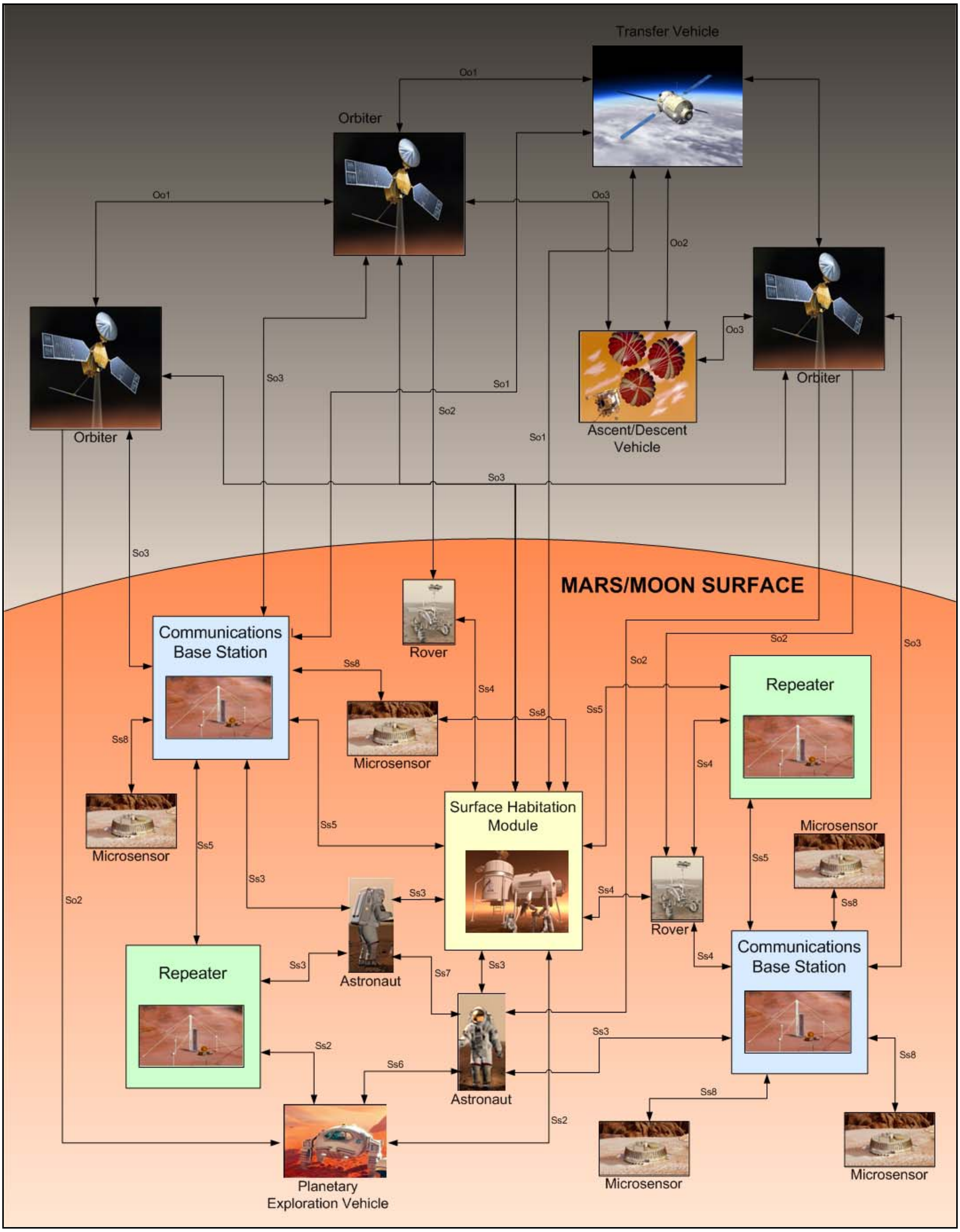


*Figure 1: PLANCOM Reference Scenario*

# TRANSMITTED SIGNAL

Figure 2 shows the high-level architecture of the OFDMA transmitter to be used in the different PLANCOM system element. Before the multiplexing of the data streams from the different services channels in the OFDM symbol, channel coding and symbols mapping are applied for each one separately. Depending on the data rate and BER requirements, the expected coverage, and the environment conditions, a different coding and modulation will be selected for each service. The channel coding includes Reed-Solomon and Convolutional redundancy. The coded bits are mapped in the corresponding symbols in the selected modulation constellation. This configuration allows a high flexibility in the terms of data rate, occupied bandwidth, and $E_b/N_0$, allowing the utilisation of the same signal architecture for the different system elements in the proposed scenario.

The mapped symbols from the different services are then assigned to OFDMA slots, and the corresponding carriers in each transmitted symbol is assigned following a PUSC channelisation approach. Each OFDM symbol will include 2K carriers in a 20 MHz frequency channel bandwidth. Guard and pilot tones are multiplexed with the data stream.

At least two OFDM symbols are introduced as preamble each a configurable number of data symbols to broadcast the multiplexing and channelisation characteristics of the transmitted signal and the navigation data. In this preamble, a PN-sequence is introduced to be used in the receiver for synchronisation purposes. To increase the navigation accuracy, the frequency of the preamble symbols can be increased.

After the OFDM symbol generation, the signal is converted to time-domain using the IFFT, prior to the introduction of the cyclic prefix, which is also a configurable parameter. The RF front-end can also be different for each system element.

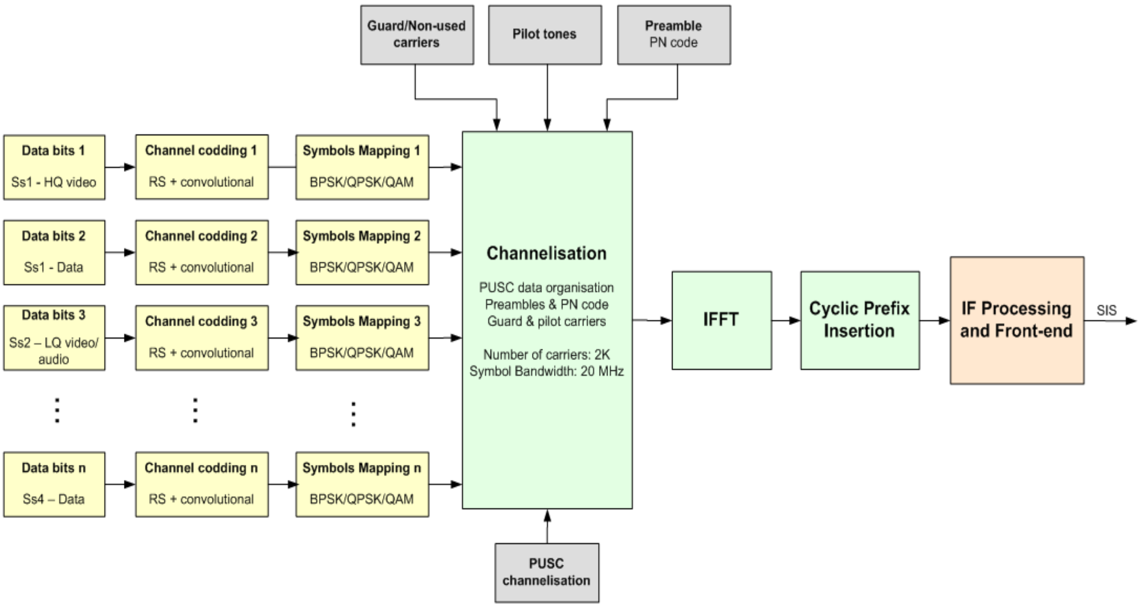


*Figure 2: High-level transmitter architecture scheme*

# RECEIVER ARCHITECTURE

Figure 2 shows the high-level architecture of the proposed receiver architecture for the PLANCOM communication and navigation terminals. Acquisition is performed correlating the incoming signal of a cyclic prefix length with previous samples to detect signal energy. Once acquired, the cyclic prefix is removed prior to FFT to obtain the data and pilot tones contained in the signal. Data carriers are then prepared to final demodulation implementing the inverse PUSC randomisation. The resulting data symbols are assigned to the corresponding transmitted channels to perform symbols de-mapping according to the modulation scheme, and channel de-coding, which include Viterbi decoding and Reed-Solomon Forward Error Correction. (FEC).

A fine synchronisation is implemented to perform symbol tracking. In this way, the acquisition ambiguity is fixed and OFDM symbols are synchronised correctly. The output of this module will allow ranging and navigation. The cyclic prefix of the early and late version of the incoming signal are correlated and used as input of the delay lock loop discriminator, which is filter prior to the signal delay correction.

The phase tracking module estimates the rotation to be applied to the demodulated symbols in order to correct the channel distortion. This rotation is calculated using the pilot tones, which allows to interpolate the phase error in all the OFDM symbol carriers.

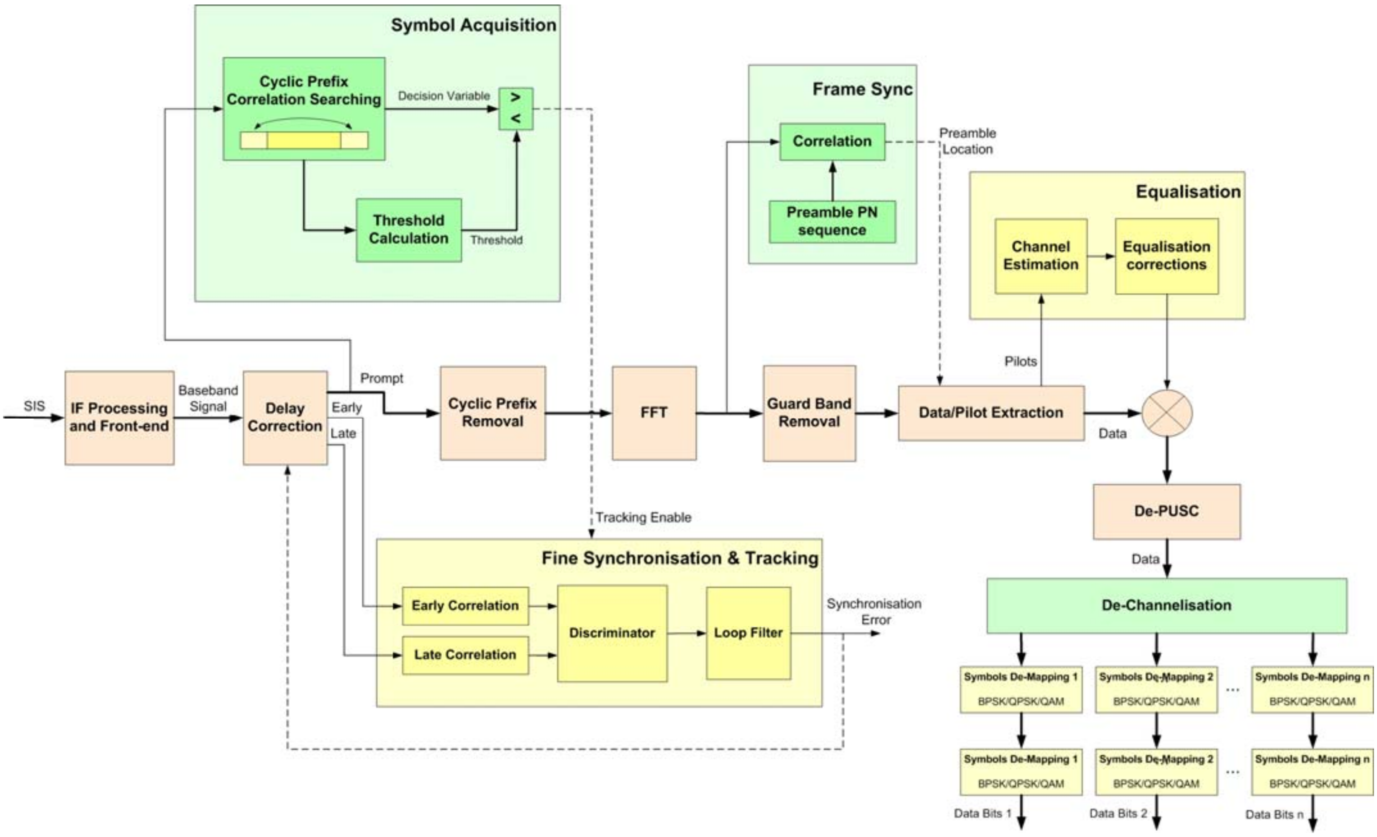


*Figure 3: High-level receiver architecture scheme*

# NAVIGATION APPROACH

The Communication Base Stations (CBS), the Surface Habitation Module (SHM), and the repeaters will be used as fixed elements to provide ground navigation signals to Planetary Exploration Vehicles (PEV), Rovers, and Astronauts. The use of PEV as mobile navigation signal transmitters to allow positioning of Astronauts and other PEVs when no enough fixed elements are available will also be considered. The use of a mobile element to navigate will involve a considerable degradation of the position performances. Orbiters will provide navigation signals to allow absolute non-real time positioning to other system elements.

A short range scenario corresponds to ground links up to 8 km length (*d*), while long range includes ground links from 8 to 30 km length. Orbit relay links are long-range scenarios with planetary scale distances. The proposed infrastructure allows relative real time and absolute non-real time navigation to PEVs, Astronauts and Rovers. SMH and CBS initial fixed positions are calibrated using orbit relays. Table 3 summarises the navigation requirements for the different system elements of the specified scenario.

| **System Element** (Slaves) | **Links ID** | **Nav. Tx** (Master) | **Coverage** | **Position Requirements** | | | |
|---|---|---|---|---|---|---|---|
| | | | | **Strategy** | **Solution Rate** | **TTFF** | **Accuracy 1-σ** |
| **PEV** | **Ss2 (Ss1)*** | SHM, CBS, Repeater, (PEV)* | Short *d* < 8km | Real-time, relative | 1-10 s | 60 s | 10 m |
| | | | Long 8km < *d* < 30 km | Real-time, relative | 1-10 s | 90 s | 100 m |
| | **So2** | Orbiters | Orbit | Non real-time, absolute | - | - | 500 m |
| **Astronaut** | **Ss3 (Ss6)*** | SHM, CBS, Repeater, (PEV)* | Short *d* < 8km | Real-time, relative | 1-10 s | 60 s | 10 m |
| | **So2** | Orbiters | Orbit | Non real-time, absolute | - | - | 1 km |
| **Rover** | **Ss4** | SHM, CBS, Repeater | Short *d* < 8km | Real-time, relative | 30-60 s | 300 s | 10 m |
| | | | Long 8km < *d* < 30 km | Real-time, relative | 30-60 s | 300 s | 100 m |
| | **So2** | Orbiters | Orbit | Non real-time, absolute | - | - | 1 Km |
| **Ascent/Descent Vehicle** | **Oo3** | Orbiters | Orbit | Non real-time, absolute (real-time if possible) | - | - | < 500 m |
| **SHM/CBS** | **So3** | Orbiters | Orbit | Non real-time, absolute | Calibration | | <1 m (TBD) |
| **Repeater** | **Ss5** | SHM, CBS | Long 8km < *d* < 30 km | Non real-time, relative | Calibration | | <1 m (TBD) |

(*) Possible use of PEVs as transmitters of navigation signals. Navigation performance is degraded above the requirements.

*Table 3: Position requirements*

# Navigation strategy

The integrated signal to be specified during the project will allow navigation using the Time of Arrival (TOA) estimated during the fine timing tracking of the OFDM signalling. Several navigation strategies will be considerer in the Moon/Mars scenarios for ground bases calibration, ground relative real-time navigation, and absolute positioning.

## ❑ Ground Transmitters calibration

The Surface Habitation Module and the Communication Base Station will be calibrated in order to determine precisely their position in the Moon/Mars surface. The exact position of this fixed elements, which are used as Master transmitters for ground navigation, will be broadcast to the mobile elements to allow navigation. An accuracy determination of these positions will be very important to avoid performance degradation in the final solution.

This initial calibration will be performed using the range signals transmitted by the orbiters. The strategy foreseen is a non-real time absolute positioning with advance tracking algorithms and error correction models. In the Moon, the possibility of using GPS signals from the Earth satellites as an additional range observable for calibration will be studied. The position of the repeaters will be fixed using the CBS/SHM ranging signal.

## ❑ Relative real-time 2-D navigation

Short-range real-time relative navigation will be done with respect to a local reference frame. Several “Master” units designated as transmitters (SHM, CBS, and probably PEVs) will provide TOA navigation to “Slave” units operating as receivers (PEVs, astronauts, and rovers). Master units transmit a TOA message in the integrated PN-OFMD signal from which the time of arrival at the “Slave” unit can be precisely determined. A message will be also sent including the precise time of transmission of the TOA message and the precise location of the Master unit based on the initial calibration using orbit relays.

The TOA will be computed used pseudorange measurements obtained with the proposed OFDM fine tracking synchronisation technique. The time-of-arrival differenced with the time-of-transmission provides the Slave unit with a range observation from each of the Master units’ locations, which are used to solve the position of the Slave. As it discussed in Section 0, the geometry of the TOA observations (DOP) from ground base stations allows 2-D navigation.

## ❑ Absolute non-real time positioning

Astronauts, rovers, and PEVs will be capable to use the orbiters navigation signals to calculate their position using a non-real time absolute location strategy. Planetary ascent/descent vehicles will also take benefit of these orbit relays to obtain position information. In Moon scenarios, the availability and convenience of using the Earth GPS signal as additional ranging observable will be considered.

The absolute navigation will be performed with respect to a Planet-Centred Planet-Fixed (PCPF) reference frame. It will be capable to provide, in a reasonable time, positioning information to the mobile ground elements using the navigation signals from the orbit relays. Specific algorithms based on cumulative satellite passage to achieve this navigation with a limited number of visible satellites are envisaged. In principle, this cumulative navigation will be based on pseudorange observations.

# Geometry Analysis

The number of base stations required to allow surface navigation is discussed in this chapter analysing the Dilution of Precision (DOP) in the area of influence. Since in most situations, the different users in the surface will navigate using ground stations, a 3-D navigation is not possible with enough precision due to the geometry between surface elements. Even increasing the height of one antenna to improve the performance, the results are far from the identified accuracy requirements.

Assuming that Mars and Moon topographic maps are available, 2-D navigation is proposed. In this way, the receiver will calculate its longitude and latitude, obtaining the height from stored maps if required. This 2-D navigation needs at least 3 stations to obtain the position, although 4 bases are recommended.

Figure 4 shows the 2-D DOP obtained in a surface area considering 3 and 4 bases. It can be observed that if the user is able to set links with 3 bases, accurate navigation can be performed only inside the area defined by these stations. If four bases are visible, it is possible the estimation of a confidence position outside this area.

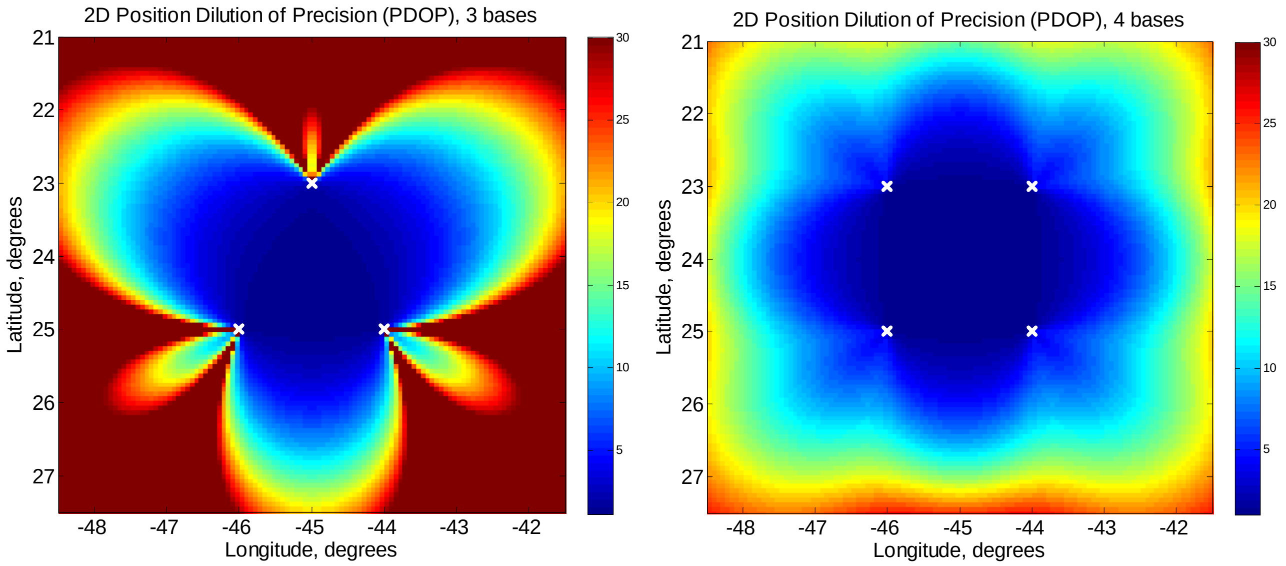


*Figure 4: 2-D Dilution of Precision considering 3 and 4 bases.*

This geometry analysis is independent from the signal used to obtain the observables. This approach will define the user equivalent range error (UERE) in the measurements that will depend on the waveform characteristics, the propagation channels, or the synchronisation capabilities of the system. The final navigation accuracy can be estimated as:

$$Accuracy = DOP \cdot UERE.$$

The DOP is defined as a function of the visible surface base stations. The minimum DOP obtained using 4 bases is 1.0041, while with 3 available bases the minimum DOP is 1.1553. In this document, the 1-sigma UERE is calculated taking into account the WiMAX signal characteristics and the environment conditions defined in Section 0. The number of visible stations is obtained from the coverage analysis in Section 0. From this inputs, the final position accuracy can be easily estimated.

# ENVIRONMENT DEFINITION

Several locations with different geological characteristics in the Moon and in Mars have been selected according to previous studies carried out to find the most promising landing sites taking into account their scientific interest and feasibility issues. The selected locations are summarised in Table 4. A representation of the map of Mars is displayed in Figure 5 (white rectangles indicate selected locations).

| | **Location #1 Moon** | **Location #2 Mars Plain** | **Location #3 Mars Mountain** | **Location #4 Mars Canyon** |
|---|---|---|---|---|
| **Location** | Moon | Mars | Mars | Mars |
| **Coordinates** | Shackleton crater<br>89.9° S, 0.0° E | Chryse Planitia<br>45º W, 24º N | Sinus Sabaeus<br>25º E, 8º S | Candor Chasma 73º W, 9º S) |

*Table 4: Scenario locations*

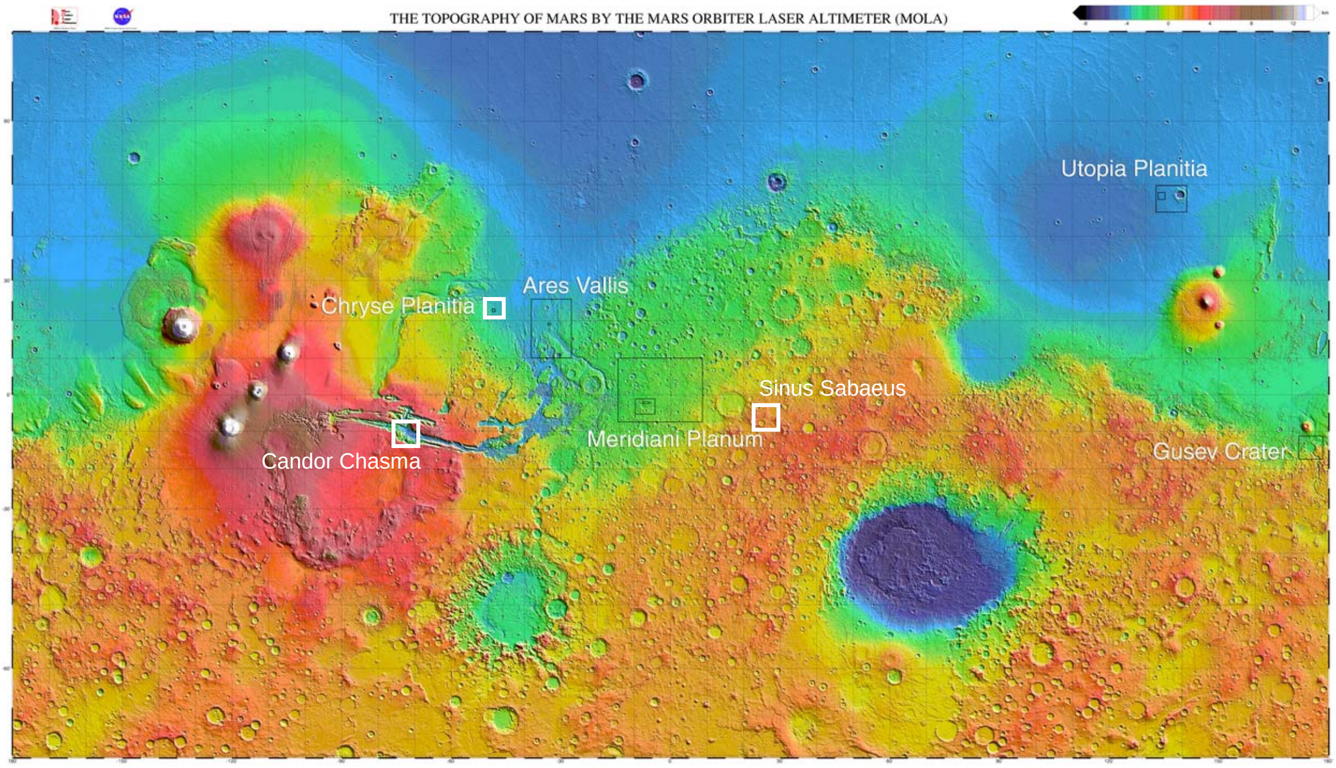


*Figure 5: Topography of Mars (MOLA data). White rectangles indicate selected locations.*

The Modified Stanford University Interim (SUI) channel models will be used to characterise the multipath for the WIMAX signalling. Table 5 shows the SUI channel model selected for each of the PLANCOM locations and for short- and long-range links. Corrections in the Doppler bandwidth of the channel model taps are applied for mobile users. These modifications depend on the maximum relative velocity between the users. Table 6 shows the Doppler values to be added to the default SUI Doppler parameters considering a carrier frequency of 2250 MHz and the maximum expected users velocities. Finally, Table 7 shows a summary of the 32 scenarios that in principle will be simulated in the frame of the PLANCOM project.

| | **Location** | **Channel Model** | |
|---|---|---|---|
| | | **Short (d < 8 Km)** | **Long (8 Km < d < 30 Km)** |
| **Moon** | **Shackleton crater** | **SUI - 3** | **SUI - 4** |
| **Mars** | **Chryse Planitia** | **SUI - 1** | **SUI - 2** |
| | **Sinus Sabaeus (Mountain)** | **SUI - 3** | **SUI - 4** |
| | **Candor Chusma (Canyon)** | **SUI - 5** | **SUI - 6** |

*Table 5: SUI channel allocation in each location*

| **Link** | **ID** | **Coverage** | **Max. Relative velocity** | **Tap Doppler** |
|---|---|---|---|---|
| **PEV ↔ PEV** | **Ss1** | Short/Long | 120 Km/h | SUI + 5 Hz |
| **PEV ↔ Base** | **Ss2** | Short/Long | 60 Km/h | SUI + 2 Hz |
| **Astronaut ↔ Base** | **Ss3** | Short | 10 Km/h | SUI + 1 Hz |
| **Rover ↔ Base** | **Ss4** | Short/Long | 10 Km/h | SUI + 1 Hz |
| **Base ↔ Base** | **Ss5** | Short/Long | 0 m/s | SUI model |
| **PEV ↔ Astronaut** | **Ss6** | Short | 60 Km/h | SUI + 2 Hz |
| **Astronaut ↔ Astronaut** | **Ss7** | Short | 10 Km/h | SUI + 1 Hz |
| **Microsensor ↔ Base** | **Ss8** | Short | 0 m/s | SUI model |

*Table 6: Doppler bandwidth correction for mobile users*

| **Link** | **ID** | **Range** | **Location** | | | |
|---|---|---|---|---|---|---|
| | | | **Moon Shackleton crater** | **Mars Chryse Planitia** | **Mars Sinus Sabaeus** | **Mars Candor Chasma** |
| **PEV ↔ PEV** | **Ss1** | **Short** | **Env 1**: SUI3 + 5 Hz | **Env 9**: SUI1 + 5 Hz | **Env 17**: SUI3 + 5 Hz | **Env 25**: SUI5 + 5 Hz |
| | | **Long** | **Env 2**: SUI4 + 5 Hz | **Env 10**: SUI2 + 5 Hz | **Env 18**: SUI4 + 5 Hz | **Env 26**: SUI6 + 5 Hz |
| **PEV ↔ Astronaut**<br>**PEV ↔ Base** | **Ss2**<br>**Ss6** | **Short** | **Env 3**: SUI3 + 2 Hz | **Env 11**: SUI1 + 2 Hz | **Env 19**: SUI3 + 2 Hz | **Env 27**: SUI5 + 2 Hz |
| | | **Long** | **Env 4**: SUI4 + 2 Hz | **Env 12:** SUI2 + 2 Hz | **Env 20**: SUI4 + 2 Hz | **Env 28**: SUI6 + 2 Hz |
| **Astronaut ↔ Base**<br>**Rover ↔ Base**<br>**Astronaut ↔ Astronaut** | **Ss3**<br>**Ss4**<br>**Ss7** | **Short** | **Env 5**: SUI3 + 1 Hz | **Env 13**: SUI1 + 1 Hz | **Env 21**: SUI3 + 1 Hz | **Env 29**: SUI5 + 1 Hz |
| | | **Long** | **Env 6**: SUI4 + 1 Hz | **Env 14**: SUI2 + 1 Hz | **Env 22**: SUI4 + 1 Hz | **Env 30**: SUI6 + 1 Hz |
| **Base ↔ Base**<br>**Microsensor ↔ Base** | **Ss5**<br>**Ss8** | **Short** | **Env 7**: SUI3 | **Env 15**: SUI1 | **Env 23**: SUI3 | **Env 31**: SUI5 |
| | | **Long** | **Env 8**: SUI4 | **Env 16**: SUI2 | **Env 24**: SUI4 | **Env 32**: SUI6 |

*Table 7: Simulation scenarios*

# PLANCOM INTEGRATED SIGNAL SIMULATOR (PLANIS)

PLANIS (PLANCOM Integrated Signal Simulator) is a simulator developed by DEIMOS SPACE S.L. in the frame of the PLANCOM project. Its main purpose is to perform the simulation of the planetary navigation and communication signal based on the WIMAX standard. The software has been implemented in Matlab/Simulink ™ R2006b, and requires the Signal Processing Toolbox and Blockset, and the Communication blockset.

After entering “PLANIS” in the Matlab command line, Figure 6 with the high-level modules of the simulator appears. It can be observed the transmitter, the propagation channel, and the receiver main blocks of the software. The simulation time can be selected in the Simulink icons bar.

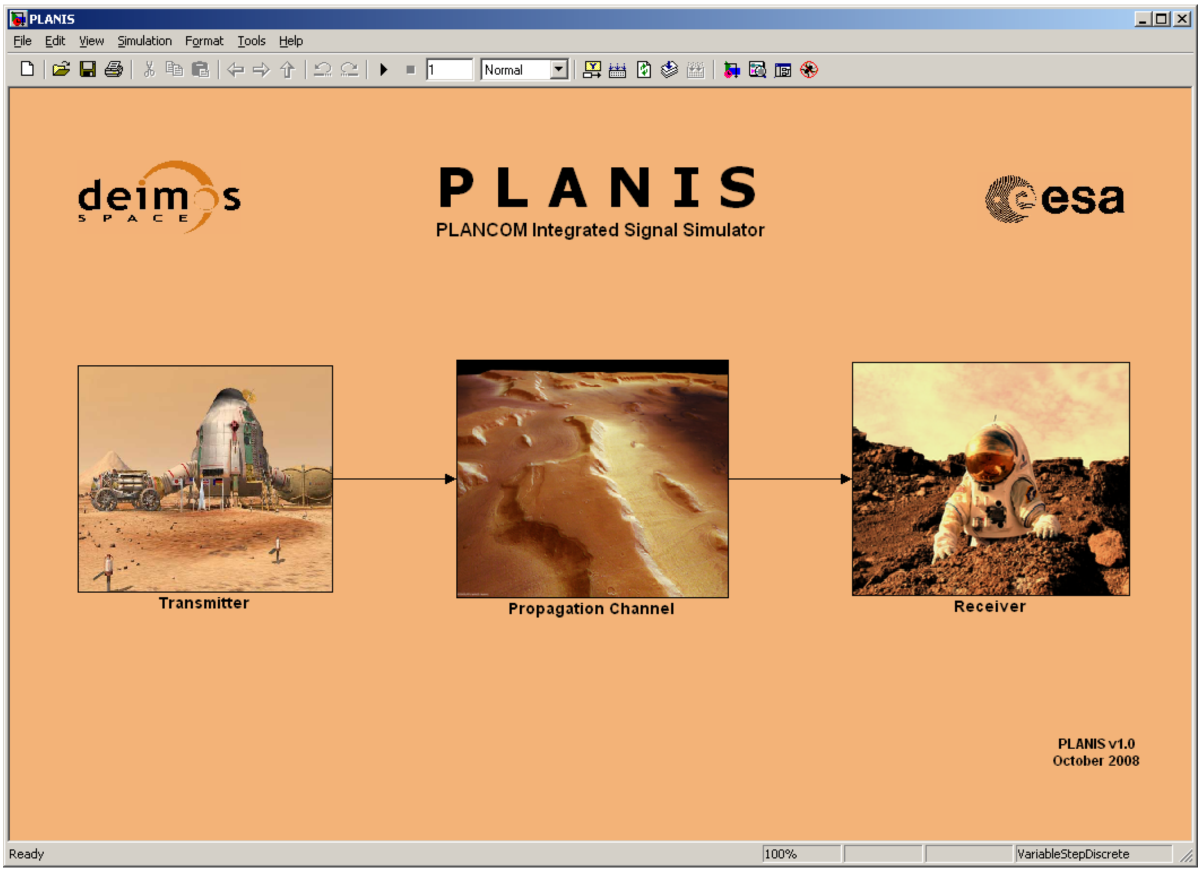


*Figure 6: PLANIS Main window*

# COMMUNICATION PERFORMANCE

Figure 7 shows a first simulation performed only in AWGN environment to assess the correct behaviour of the PLANIS simulator. It can be observed which is the minimum achievable BER in this ideal environment, without multipath, for each of the modulations and channel coding possibilities.

From Figure 8 to Figure 19, the BER vs $E_b/N_0$ for some of the proposed scenario is shown.

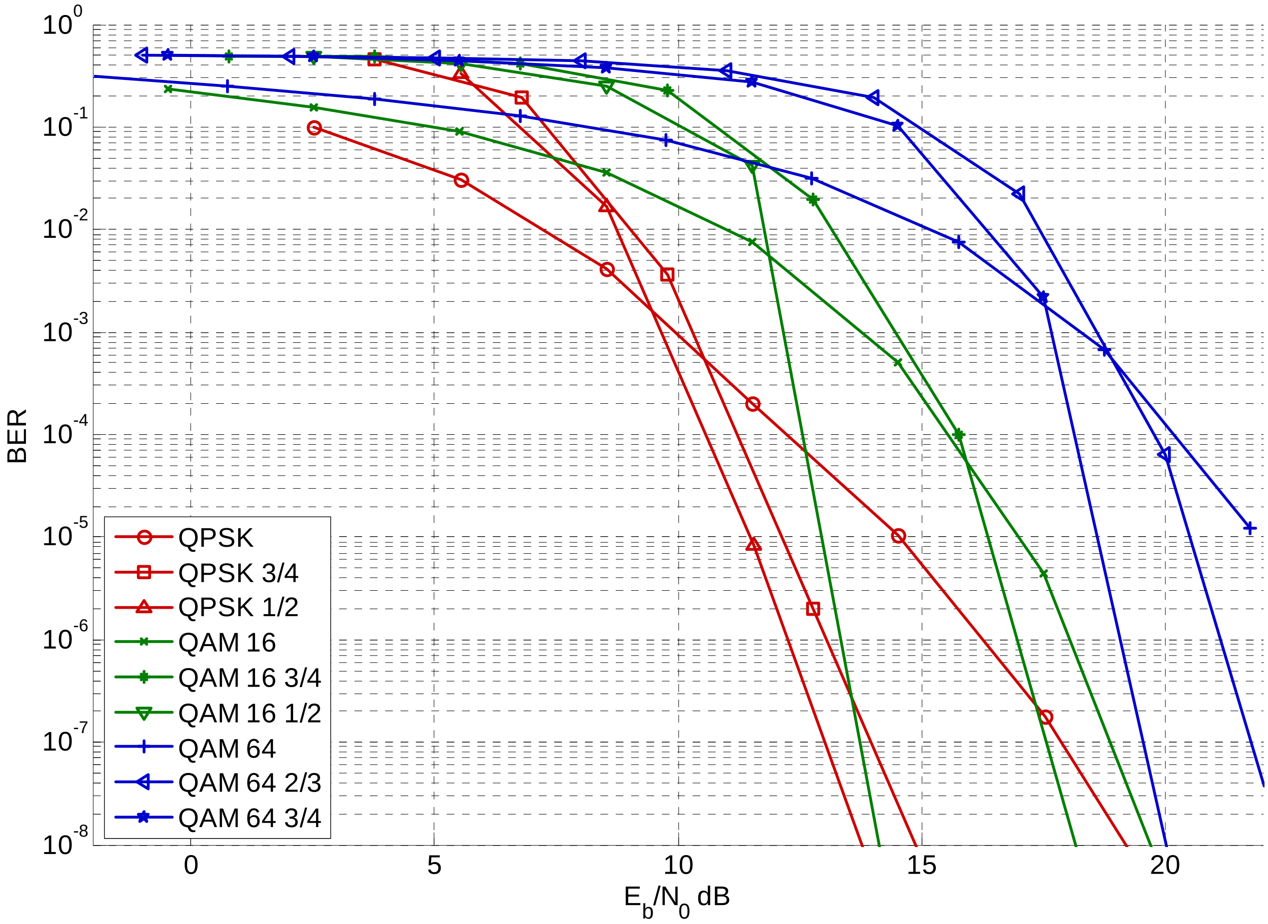


*Figure 7: BER vs. $E_b/N_0$ for AWGN channel*

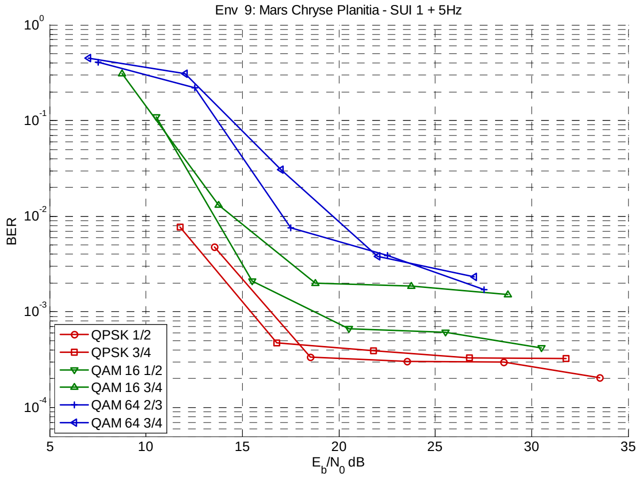


*Figure 8: BER vs. $E_b/N_0$ for Env. 9 (SUI 1 + 5 Hz)*

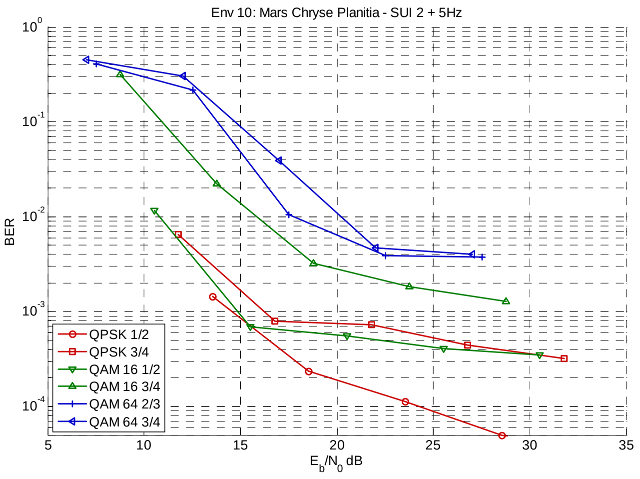


*Figure 9: BER vs. $E_b/N_0$ for Env. 10 (SUI 2 + 5 Hz)*

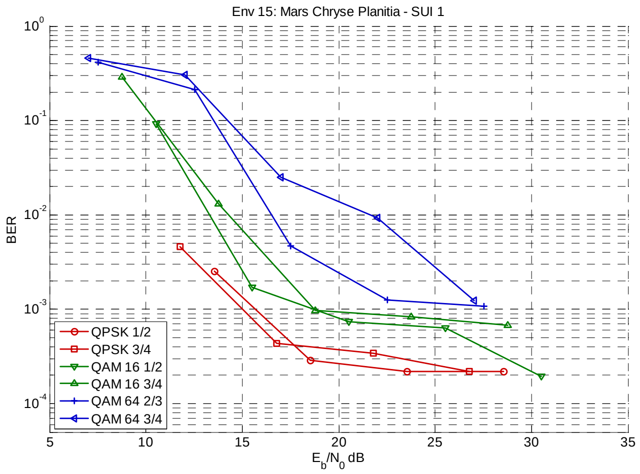


*Figure 10: BER vs. $E_b/N_0$ for Env. 15 (SUI 1)*

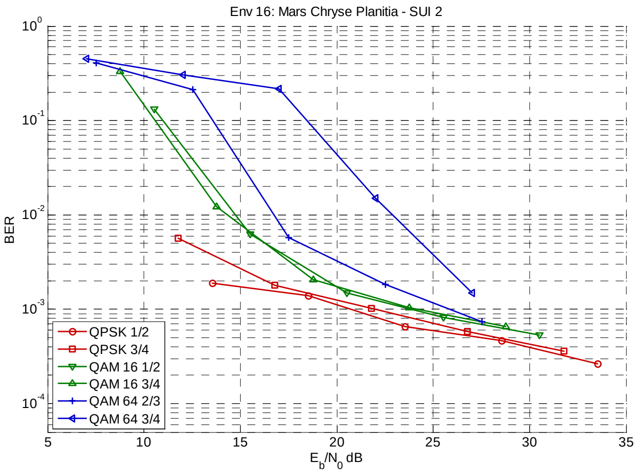


*Figure 11: BER vs. $E_b/N_0$ for Env. 16 (SUI 2)*

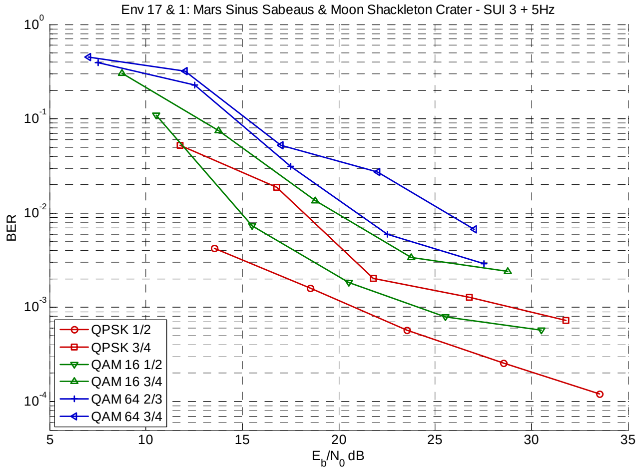


*Figure 12: BER vs. $E_b/N_0$ for Env. 17 & 1 (SUI 3 + 5 Hz)*

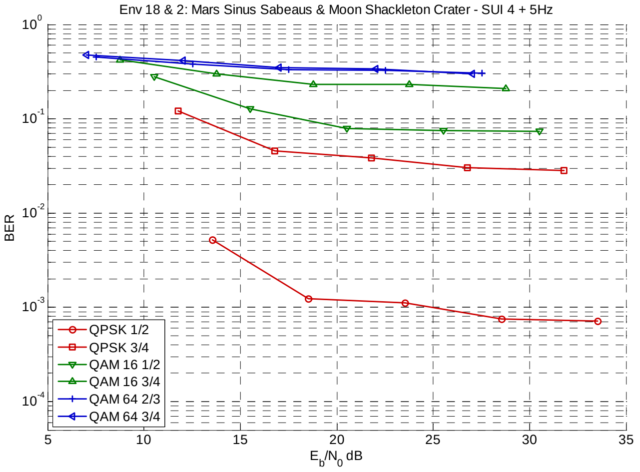


*Figure 13: BER vs. $E_b/N_0$ for Env. 18 & 2 (SUI 4 + 5 Hz)*

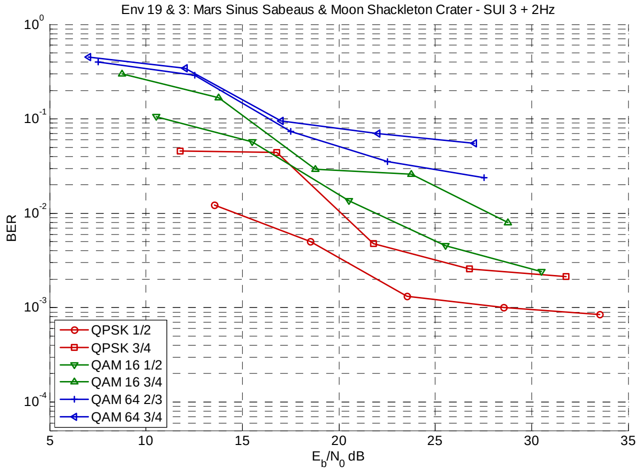


Figure 14: BER vs. $E_b/N_0$ for Env. 19 & 3 (SUI 3 + 2 Hz)

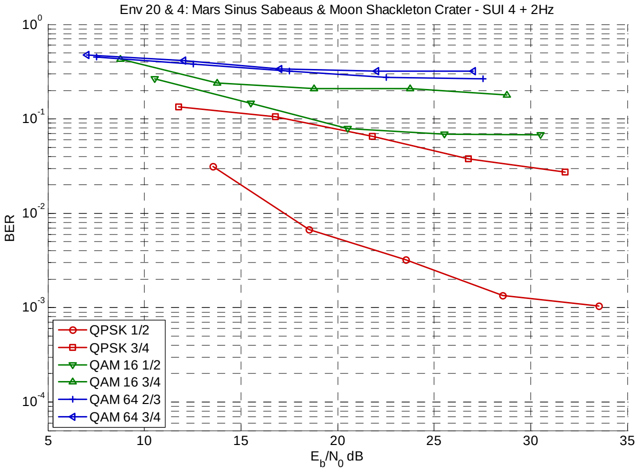


Figure 15: BER vs. $E_b/N_0$ for Env. 20 & 4 (SUI 4 + 2 Hz)

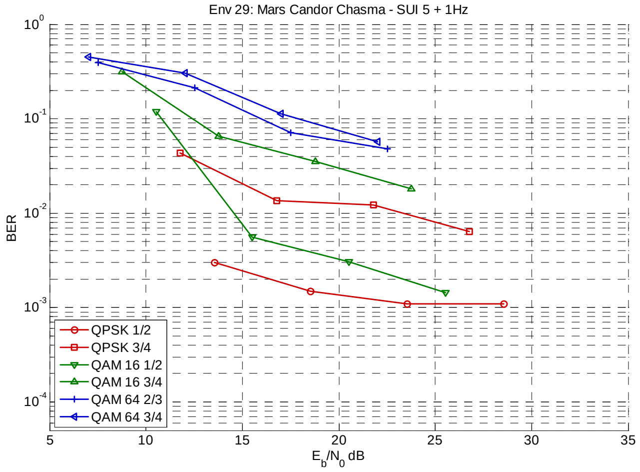


Figure 16: BER vs. $E_b/N_0$ for Env. 29 (SUI 5 + 1 Hz)

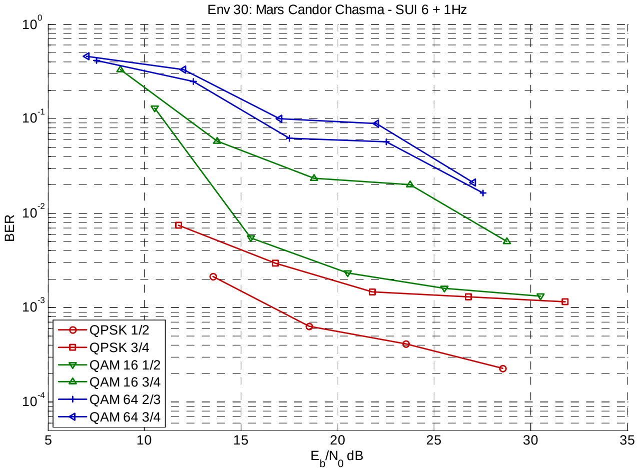


Figure 17: BER vs. $E_b/N_0$ for Env. 30 (SUI 6 + 1 Hz)

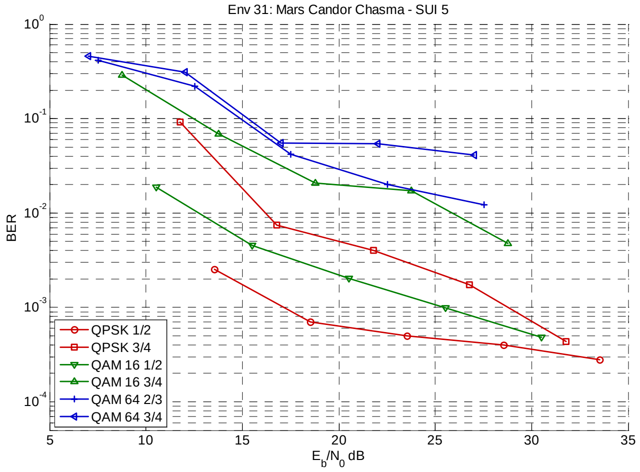


Figure 18: BER vs. $E_b/N_0$ for Env. 31 (SUI 5)

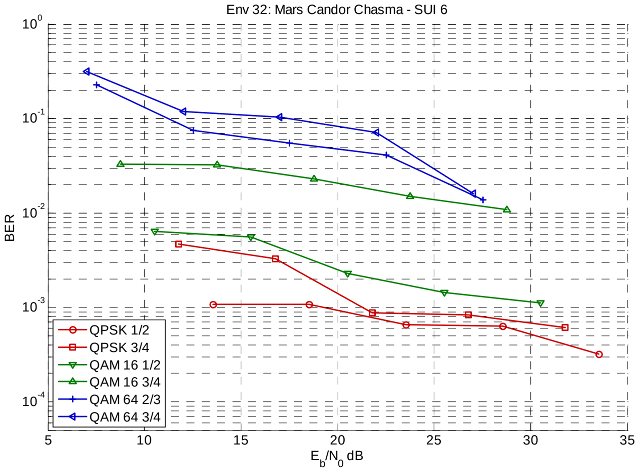


Figure 19: BER vs. $E_b/N_0$ for Env. 32 (SUI 6)

# NAVIGATION PERFORMANCE

The performed simulation also provides the synchronisation error, allowing to obtain the 1-σ error as a function of $C/N_0$ in the navigation observables for each scenario (Figure 20 to Figure 25) .

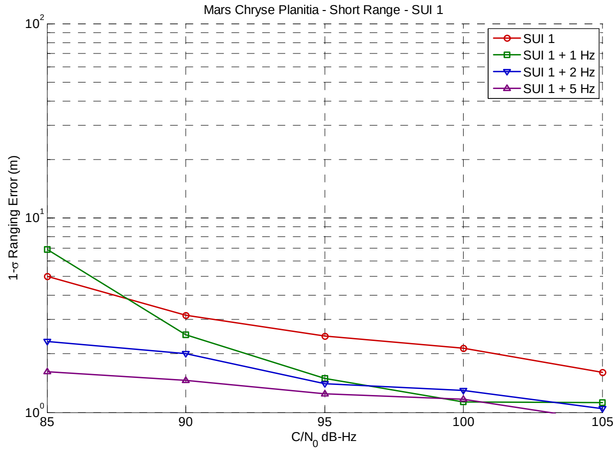


*Figure 20: Ranging Error vs. $C/N_0$ for Env. 9, 11, 13, and 15 (SUI 1)*

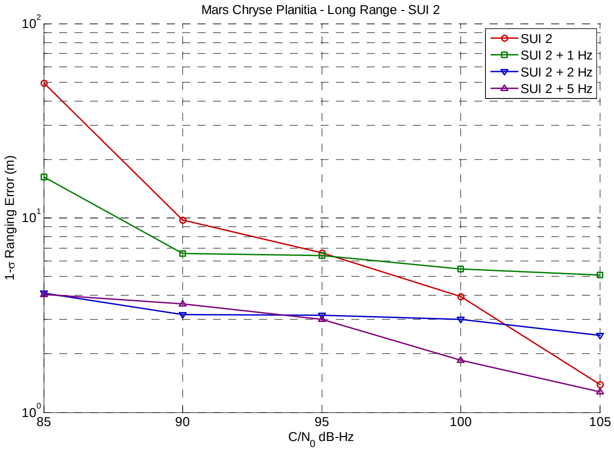


*Figure 21: Ranging Error vs. $C/N_0$ for Env. 10, 12, 14, and 16 (SUI 2)*

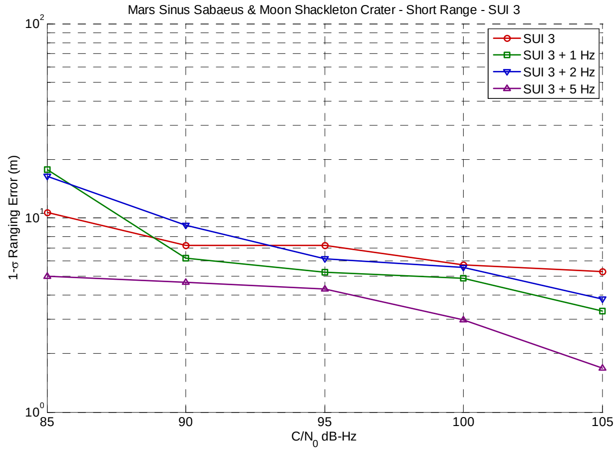


*Figure 22: Ranging Error vs. $C/N_0$ for Env. 17, 19, 21, and 23 (SUI 3)*

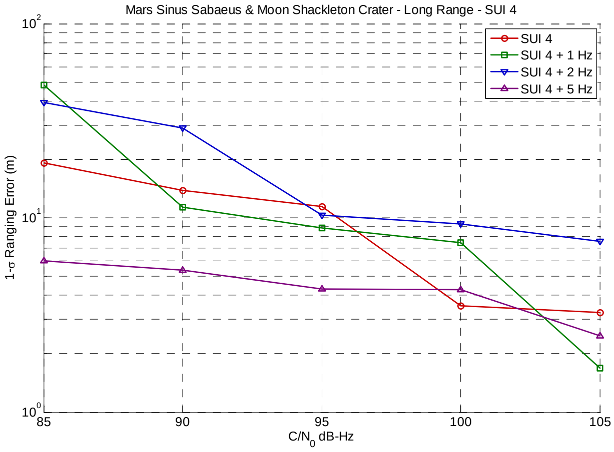


*Figure 23: Ranging Error vs. $C/N_0$ for Env. 18, 20, 22, and 24 (SUI 4)*

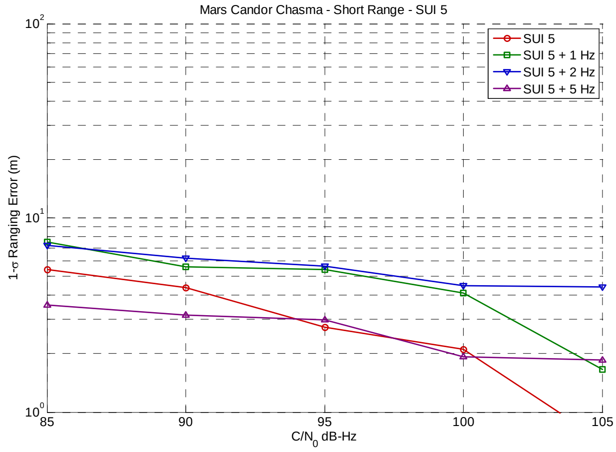


*Figure 24: Ranging Error vs. $C/N_0$ for Env. 25, 27, 29, and 31 (SUI 5)*

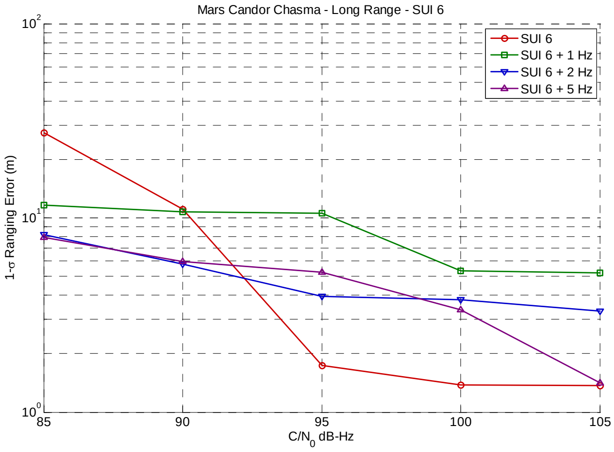


*Figure 25: Ranging Error vs. $C/N_0$ for Env. 26, 28, 30, and 32 (SUI 6)*

# SIGNAL RECOMMENDATIONS AND RESULTS ANALYSIS

Table 8 shows a summary of the signal simulation results. For each scenario, a combination of modulation and channel coding is recommended for a given BER and $E_b/N_0$. This is selected checking the most efficient modulation that covers this specification. Selection of a more efficient modulation and coding results in a reduction of the required occupied bandwidth for the same energy per bit ($E_b$). In this way, data rate requirements will be achieved increasing this bandwidth as a function of the environment conditions.

Results in Table 8 cover both short (< 8 km) and long range links (8 km< d <30 km). These results can also be used for orbit-to-surface links, taking into account the additional free-space propagation losses in the estimation of the required transmitted power for a given $E_b/N_0$ and the reduced data rate requirements.

In several results in Figure 8 to Figure 19 it can be observed that the BER is not reduced bellow $10^{-4}$, even increasing the signal power. That is due to the multipath effect in the received waveform for difficult environments in Moon and Mars. Since it is not possible to increase the system perform to fulfil the requirements, two options are recommended as output of this study:

- Relax the BER requirements for some of the services: audio, data, and biomedical.
- Include some redundancy and additional acknowledge at protocol level, loosing efficiency, but allowing to repeat wrong packages to increase the overall BER. This is especially important for data involving astronauts' biomedical data.

The 1-σ ranging error (or User Equivalent Range Error), which is obtained from the fine synchronisation algorithm in the receiver tracking stage, is also provided for a $C/N_0$ of 80 dB-Hz. It must be noted that this value is the same for all the service channels in the same signal.

An estimation of the position accuracy for this case using the UERExDOP approach described in Section 0 is also provided, assuming the availability of 3 or 4 base stations and a conservative value of the Dilution of Precision of 2. The results show that the position accuracy fulfils the requirements for long-range operations in all the proposed scenarios (< 100 m, see Table 3), while the short-range requirements are bellow 20 meters in all the cases, and below 10 meters for the Mars Chryse Planitia.

Anyway, it must be considered that the Moon crater, and Mars mountain and canyon are the most possible difficult environments. In additional to possible high errors in the estimation of the position accuracy, visibility problems with the ground base stations can reduce the availability of estimation of the position accuracy. In the following section, this issue is deeply analysed with the coverage analysis simulations obtained with the Wigiplan tool. A relation between the received signal power levels and the $E_b/N_0$ in the signal plots can be easily derived during the real design and implementation of the in-situ navigation and communication system.

With respect the time-to-first-fix, since the proposed OFDMA based acquisition and tracking converge quite fast, no problems are expected to fulfil the requirements. The solution rate is not an issue due to the fast rate of the incoming symbols.

| Scenario | | Model | Link - Range | BER=$10^{-3}$ Eb/$N_0$=15dB | BER=$10^{-3}$ Eb/$N_0$=20dB | BER=$10^{-4}$ Eb/$N_0$=25dB | 1-σ Ranging Error C/$N_0$=90dB-Hz | Est.Position Accuracy C/$N_0$=90dB-Hz |
|---|---|---|---|---|---|---|---|---|
| Mars Chryse Planitia | Env 9 | SUI 1 + 5Hz | Ss1 - Short | QPSK 1/2 | 16QAM 1/2 | - | 2 m | **4 m** |
| | Env 10 | SUI 2 + 5Hz | Ss1 - Long | 16QAM 1/2 | 16QAM 1/2 | QPSK 1/2 | 3 m | **6 m** |
| | Env 11 | SUI 1 + 2Hz | Ss2,6 - Short | QPSK 1/2 | QPSK 3/4 | - | 2 m | **4 m** |
| | Env 12 | SUI 2 + 2Hz | Ss2,6 - Long | QPSK 1/2 | 16QAM 1/2 | QPSK 1/2 | 3 m | **6 m** |
| | Env 13 | SUI 1 + 1Hz | Ss3,4,7 - Short | QPSK 1/2 | QPSK 3/4 | - | 3 m | **6 m** |
| | Env 14 | SUI 2 + 1Hz | Ss3,4,7 - Long | - | QPSK 1/2 | - | 6 m | **12 m** |
| | Env 15 | SUI 1 | Ss5,8 - Short | QPSK 3/4 | 16QAM 3/4 | QPSK 1/2 | 3 m | **6 m** |
| | Env 16 | SUI 2 | Ss5,8 - Long | QPSK 1/2 | QPSK 3/4 | - | 10 m | **20 m** |
| **Scenario** | | **Model** | **Link - Range** | **BER=$10^{-2}$ Eb/N0=15dB** | **BER=$10^{-2}$ Eb/N0=20dB** | **BER=$10^{-3}$ Eb/N0=25dB** | **1-σ Ranging Error C/$N_0$=90dB-Hz** | **Est.Position Accuracy C/$N_0$=90dB-Hz** |
| Mars Sinus Sabaeus Moon Shackleton Crater | Env 1&17 | SUI 3 + 5Hz | Ss1 - Short | 64QAM 1/2 | 64QAM 3/4 | 64QAM 1/2 | 6 m | **12 m** |
| | Env 2&18 | SUI 4 + 5Hz | Ss1 - Long | QPSK 1/2 | QPSK 1/2 | QPSK 1/2 | 8 m | **16 m** |
| | Env 3&19 | SUI 3 + 2Hz | Ss2,6 - Short | QPSK 1/2 | QPSK 3/4 | QPSK 1/2 | 8 m | **16 m** |
| | Env 4&20 | SUI 4 + 2Hz | Ss2,6 - Long | QPSK 1/2 | QPSK 1/2 | - | 30 m | **60 m** |
| | Env 5&21 | SUI 3 + 1Hz | Ss3,4,7 - Short | 16QAM 1/2 | 16QAM 1/2 | QPSK 1/2 | 5 m | **10 m** |
| | Env 6&22 | SUI 4 + 1Hz | Ss3,4,7 - Long | QPSK 1/2 | QPSK 1/2 | QPSK 1/2 | 11 m | **22 m** |
| | Env 7&23 | SUI 3 | Ss5,8 - Short | QPSK 1/2 | 16QAM 1/2 | QPSK 1/2 | 6 m | **12 m** |
| | Env 8&24 | SUI 4 | Ss5,8 - Long | QPSK 1/2 | QPSK 3/4 | QPSK 1/2 | 15 m | **30 m** |
| Mars Candor Chasma | Env 25 | SUI 5 + 5Hz | Ss1 - Short | 16QAM 1/2 | 64QAM 2/3 | 16QAM 1/2 | 3 m | **6 m** |
| | Env 26 | SUI 6 + 5Hz | Ss1 - Long | 16QAM 1/2 | 64QAM 2/3 | 16QAM 1/2 | 6 m | **12 m** |
| | Env 27 | SUI 5 + 2Hz | Ss2,6 - Short | 16QAM 1/2 | 16QAM 3/4 | 16QAM 1/2 | 6 m | **12 m** |
| | Env 28 | SUI 6 + 2Hz | Ss2,6 - Long | QPSK 3/4 | 16QAM 3/4 | 16QAM 1/2 | 7 m | **14 m** |
| | Env 29 | SUI 5 + 1Hz | Ss3,4,7 - Short | 16QAM 1/2 | 16QAM 1/2 | 16QAM 1/2 | 6 m | **12 m** |
| | Env 30 | SUI 6 + 1Hz | Ss3,4,7 - Long | 16QAM 1/2 | 16QAM 1/2 | 16QAM 1/2 | 10 m | **20 m** |
| | Env 31 | SUI 5 | Ss5,8 - Short | 16QAM 1/2 | 16QAM 1/2 | 16QAM 1/2 | 4 m | **8 m** |
| | Env 32 | SUI 6 | Ss5,8 - Long | 16QAM 1/2 | 16QAM 1/2 | 16QAM 1/2 | 10 m | **20 m** |

*Table 8: Summary of Recommended Modulations and Coding and associated positioning accuracy*

# THE WIGIPLAN SOFTWARE TOOL

WiGIPLAN is a novel GIS based wireless planning and dimensioning tool specifically developed for non-urban areas and employing extensive GIS databases. Apart from Digital Elevation Model (DEM), the tool also employs cartography and terrain usage information. These geodatabases can be very useful for the planning process given that they can provide information on the suitability and cost of a given Base Station (BS) location site. The WiGiPLAN tool will be upgraded to cover the requirements of Mars and Moon environments, taken into account the specific propagation characteristics such of planet curvature, ionospheric effects, etc.  The tool is composed of the following five modules, that interoperate based on the user and tool needs:

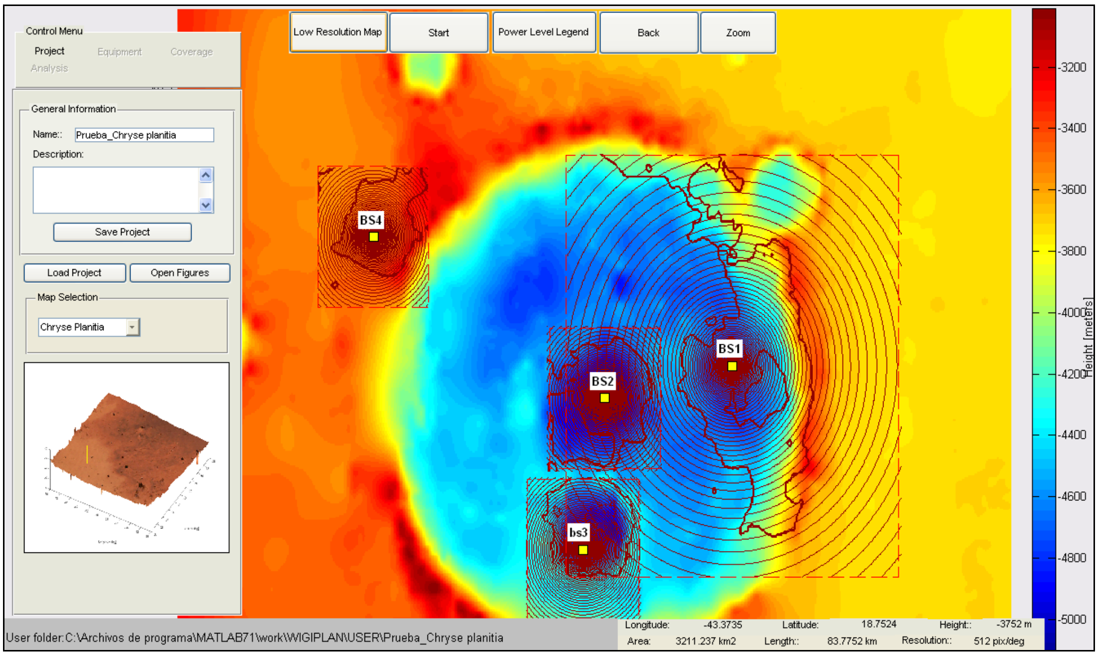
1) *User interface*: A friendly interface allows the user to control the planning process and to visualize and analyse the results of simulation. All the functionalities of the planning workflow can be accessed intuitively.

2*) Coverage computations*: This module contains a set of coverage prediction models, both for PMP (Point to Multi-Point) and for PTP (Point To Point) deployments.

3) *Mapping tool*: There are two types of information that can be displayed with the Mapping module. The first one if geographic information about the zone of interest, including terrain elevation data, clutter zones, administrative divisions, town locations, roads, electricity, topology, etc. Second, the mapping tool may be used to display the results of the simulation.

4) *Data managing*: Access, control, and managing of stored data are included in this module. On the one hand, the tool maintains databases where simulation results and geographic data are stored and modified. On the other hand, each project stores its own data concerning name, description, configuration, etc.

5) *Optimization and analysis*: The analysis module includes functionalities to analyse the coverage simulation results graphically and numerically. The optimization module allows the user to find the best locations for the base stations.



Name:: Prueba_Chryse planitia
Description:
Map Selection: Chryse Planitia

User folder:C:\Archivos de programa\MATLAB71\work\WIGIPLAN\USER\Prueba_Chryse planitia

Longitude: -43.3735 Latitude: 18.7524 Height:: -3752 m
Area: 3211.237 km2 Length:: 83.7752 km Resolution:: 512 pix/deg

*Figure 26: WigiPLAN simulator*

# COVERAGE ANALYSIS RESULTS

Using the WigiPLAN tool, coverage analysis in the selected locations have been performed. In this document, some results for the Chryse Planitia are provided. The simulation has considered the elements from the following table:

| **User / Element** | **Longitude** (degrees) | **Latitude** (degrees) | **Freq.** (MHz) | **Tx Power** (dBm) | **Antenna Gain** (dB) | **Antenna Height** (m) | **Tx Losses** (dB) |
|---|---|---|---|---|---|---|---|
| Base Station | –43.8286 | 30.0134 | 2200 | 20 | 3 | 10 | 0.5 |
| Microsensor | –43.7873 | 30.0125 | 2200 | 11 | 0 | 1 | 0 |
| Rover | –43.8417 | 29.9478 | 2200 | 14 | 0 | 1 | 0 |
| Astronaut | –43.8812 | 29.9752 | 2200 | 21 | 0 | 2 | 0 |
| PEV | –43.9006 | 30.0471 | 2200 | 21 | 0 | 3 | 0 |

*Table 9: Users considered in the Chryse Planitia simulation.*

Graphically, the elements are located as shown in Figure 27. The squares indicate the map areas considered by the tool to carry out the calculations of the items. Every single element is supposed to be located in the centre of its square. Figure 28 shows the received power map in its covering area.

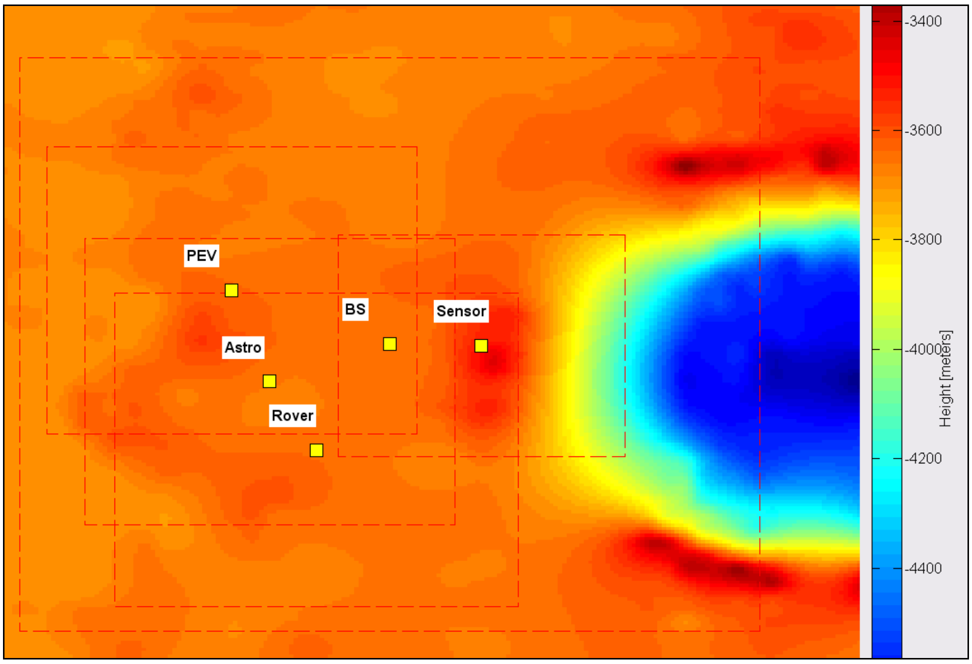
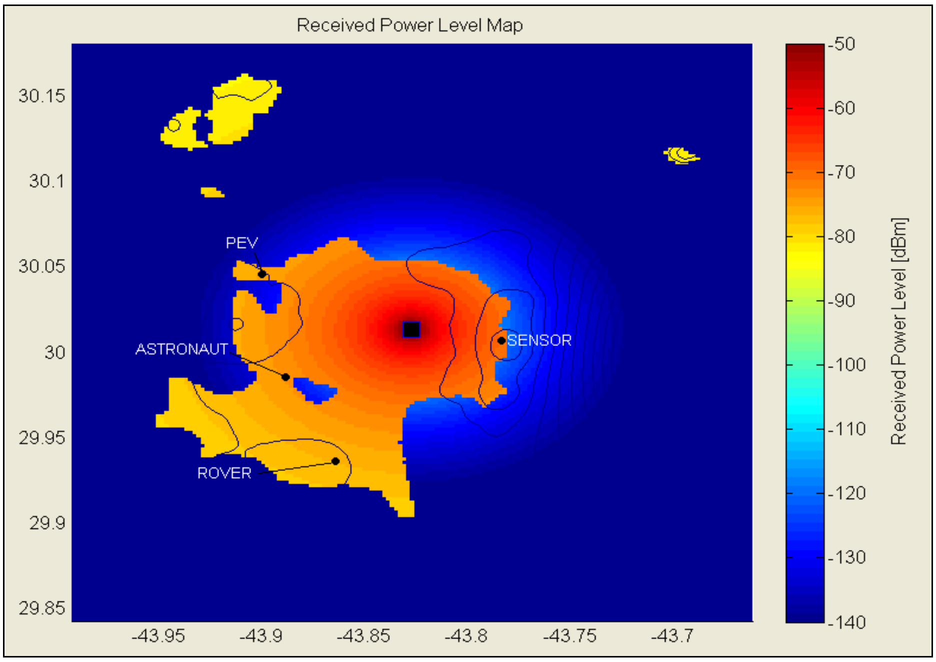


*Figure 27: Chryse Planitia simulation area*



| Parameter | Astronaut | Sensor | Rover | PEV |
|---|---|---|---|---|
| Power received | -73.62 | -69.88 | -76.68 | -75.16 |

*Figure 28: Received power by the deployed elements*

The results for all elements and other modulations are summarized in Table 10. The best results will be obtained maximizing antenna height and gain, transmission power and using high quality receivers. But the topography of the chosen site to explore appears as the main important factor that will allow the more extended coverage to all the users. A bad selection will require the deployment of repeaters or additional base extensions to reach the desired coverage.

| Link | Noise | SUI model Doppler | QPSK ½ | QPSK ¾ | 16QAM ½ | 64QAM ¾ |
|---|---|---|---|---|---|---|
| **PEV - Base** | -100dBm<br>-90 dBm | SUI1<br>2Hz | $3.6\cdot10^{-4}$<br>$1.8\cdot10^{-3}$ | $8.5\cdot10^{-4}$<br>$2.4\cdot10^{-3}$ | $6.1\cdot10^{-3}$<br>$2.4\cdot10^{-2}$ | $5.8\cdot10^{-2}$<br>$2.1\cdot10^{-1}$ |
| **Base - PEV** | -100dBm<br>-90 dBm | SUI1<br>2Hz | $3.3\cdot10^{-4}$<br>$1.5\cdot10^{-3}$ | $9.1\cdot10^{-4}$<br>$3.2\cdot10^{-3}$ | $1.7\cdot10^{-3}$<br>$5.1\cdot10^{-3}$ | $3.5\cdot10^{-2}$<br>$2.9\cdot10^{-1}$ |
| **Astronaut - Base** | -100dBm<br>-90 dBm | SUI1<br>1Hz | $2.9\cdot10^{-4}$<br>$2.0\cdot10^{-3}$ | $8.9\cdot10^{-4}$<br>$8.2\cdot10^{-3}$ | $2.6\cdot10^{-3}$<br>$4.5\cdot10^{-2}$ | $5.5\cdot10^{-2}$<br>$3.6\cdot10^{-1}$ |
| **Base - Astronaut** | -100dBm<br>-90 dBm | SUI1<br>1Hz | $2.6\cdot10^{-4}$<br>$1.4\cdot10^{-3}$ | $4.8\cdot10^{-4}$<br>$6.1\cdot10^{-3}$ | $1.1\cdot10^{-3}$<br>$2.6\cdot10^{-2}$ | $3.9\cdot10^{-2}$<br>$3.7\cdot10^{-1}$ |
| **Rover - Base** | -100dBm<br>-90 dBm | SUI1<br>1 Hz | $6.2\cdot10^{-4}$<br>$5.2\cdot10^{-3}$ | $4.1\cdot10^{-3}$<br>$3.1\cdot10^{-2}$ | $1.6\cdot10^{-2}$<br>$1.1\cdot10^{-1}$ | $2.7\cdot10^{-1}$<br>$5\cdot10^{-1}$ |
| **Base - Rover** | -100dBm<br>-90 dBm | SUI1<br>1Hz | $2.9\cdot10^{-4}$<br>$1.6\cdot10^{-3}$ | $8.1\cdot10^{-4}$<br>$7.0\cdot10^{-3}$ | $2.4\cdot10^{-3}$<br>$2.9\cdot10^{-2}$ | $5.3\cdot10^{-2}$<br>$3.7\cdot10^{-1}$ |
| **Sensor - Base** | -100dBm<br>-90 dBm | SUI1 | $2.6\cdot10^{-4}$<br>$2.5\cdot10^{-2}$ | $3.7\cdot10^{-4}$<br>$3.1\cdot10^{-2}$ | $7.8\cdot10^{-4}$<br>$2.7\cdot10^{-1}$ | $9.4\cdot10^{-3}$<br>$3.9\cdot10^{-1}$ |
| **Base - Sensor** | -100dBm<br>-90 dBm | SUI1 | $2.6\cdot10^{-4}$<br>$3.2\cdot10^{-4}$ | $3.7\cdot10^{-4}$<br>$4.1\cdot10^{-4}$ | $7.1\cdot10^{-4}$<br>$1.1\cdot10^{-3}$ | $8.6\cdot10^{-3}$<br>$1.1\cdot10^{-2}$ |

*Table 10: Chryse Planitia links BER.*

# CONCLUSIONS

In this project, a solution for an integrated communication and navigation system for in-situ operations has been proposed. Based on the WIMAX standard and using OFDMA multiplexing, the proposed signal allows duplex high-data rate communication and user positioning within the same signal.

After defining the scenarios for future missions, the links between the different system elements have been defined, deriving communication and navigation requirements for each of these links. Specific requirements for each of the elements have been finally specified.

The signal definition includes the design of the transmitter and receiver architectures, including channel coding and multiplexing, modulation, channelisation strategy, symbol and frame acquisition, fine synchronisation, equalisation using pilot tones, and data demodulation. The approach for navigation using this signal has been also discussed.

For simulation purposes, a reference scenario have been defined, including the selection of Moon and Mars location, a link budget analysis, and the definition of the multipath channel based on SUI propagation models.

Two simulators have been developed in the frame of this contract: PLANIS, which is a Matlab/Simulink sample-based simulator of the proposed OFDM signal, including the transmitter, propagation channel, and receiver; and WigiPLAN, which is a Matlab tool for coverage analysis in selected locations.

The results show excellent navigation performances using the proposed signal architecture while transmitting enough bit rate to cover all the required services. The BER floor obtained in the PLANIS simulators for the different scenarios are due to the difficult environment characterised by the SUI models. The multipath channel in the proposed locations is expected to be better than the characterised using these models.

The following activities are proposed as future developments in the frame of this activity:

- Development of a transmitter and receiver prototypes for laboratory and field tests.
- A better characterisation of the Moon/Mars scenarios in terms of multipath is recommended. Field test in Earth's similar environments are proposed.
- Implementation in the receiver of multipath mitigation techniques at antenna and signal processing levels.
- Investigate algorithms to allow constant envelope in the transmitted OFDM signals.

End of Document