USE OF THE 37-38 GHZ AND 40-40.5 GHZ KA-BANDS FOR DEEP SPACE COMMUNICATIONS

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1. INTRODUCTION

The use of the 37 to 38 GHz and 40 to 40.5 GHz frequency allocations of Ka-band is being considered for future space missions, as well as conventional X-band, S-band, and 32 GHz Ka-band, and newer technologies or higher frequency bands such as optical communications, and W-band (90 GHz).

This paper covers a wide variety of issues associated with the implementation and use of these frequency bands for deep space communications. Performance issues, such as ground station pointing stability, ground antenna gain, antenna pattern, and propagation effects such as due to atmospheric, charged-particle and space loss at 37 GHz, will be addressed in comparison to the 32 GHz Ka-band deep space allocation. Issues with the use of and competition for this spectrum also will be covered. The state of the hardware developed (or proposed) for operating in this frequency band will be covered from the standpoint of the prospects for achieving higher data rates that could be accommodated in the available bandwidth. Hardware areas to be explored include modulators, digital-to-analog converters, filters, power amplifiers, receivers, and antennas. The potential users of the frequency band will be explored as well as their anticipated methods to achieve the potential high data rates and the implications of the competition for bandwidth.

2. 37 – 38 AND 40 – 40.5 GHz Ka-BAND FREQUENCY ALLOCATIONS

For the United States, the entire 37 to 38 GHz band can be used by the Federal Government for space research, fixed and mobile communications. The portion from 37 to 37.6 GHz can be used by non-federal government entities for fixed and mobile communications, while the 37.6 to 38.6 GHz band can be used by these entities for fixed, fixed-satellite (space to Earth) and mobile communications [1].

There is currently an effort underway to study and develop a sharing methodology to allow space missions and the High Density Fixed Service (HDFS) emerging technology to share the 37-38 GHz band. From a spectrum allocation point of view, the entire 37 - 38 GHz band can be used by both Mars and Lunar missions. However, the Space Frequency Coordination Group (SFCG) recommends that the lower half of this band be reserved for human Mars missions, and for developing communications systems at the Moon in preparation for use at Mars. The upper half of this band from 37.5 to 38 GHz would be used for lunar missions, as well as for other space services.

In the Earth-to-space direction, the 40 to 40.5 GHz band is allocated for uplink (forward) and is the companion to the 37 to 38 GHz downlink return band.

In the United States, the 40.5 to 41 GHz band (shared users) is allocated for fixed satellite (space-to-Earth), broadcasting, broadcasting satellite, mobile (secondary), and fixed ground-to-ground (secondary), but not for space research.

3. PERFORMANCE AT 37 GHz

In order to assess the telecommunication performance at the 37 - 38 GHz downlink band, especially in comparison to the 32 GHz Ka-band, a list of contributions to performance enhancement or degradation is presented below and the status summarized.

a. Ground Station Pointing Stability

The ground station pointing performance is expected to degrade significantly under windy conditions at 37 GHz and is expected to be somewhat worse but not too much different, than what has been experienced at 32 GHz with DSN tracking of the Cassini spacecraft's Ka-band downlink carrier-only signal used for Radio Science. The wind can cause severe effects at 32 GHz, especially for wind speeds of 30 mph and upwards. The degree of signal degradation due to wind will depend on various factors such as ground antenna diameter, wind speed, direction of wind relative to antenna structure, and effectiveness of any wind-compensating algorithms. For smaller diameter antennas, signal degradation effects are expected to be smaller due to the larger beam size at a given frequency. When the wind gusts exceed a certain limit such as 55 mph, the large diameter antennas of the DSN are stowed (pointed vertically).

b. Ground Antenna Gain

Expected gain degradation due to RMS surface roughness at 37 GHz is about 0.8 dB at DSS-25, one of the DSN's operational 34-m diameter beam waveguide antennas at Goldstone, near Barstow, California. This is comparable to the corresponding 0.6 dB degradation expected at 32 GHz. These estimates assume an RMS surface roughness of 0.275 mm referenced to the rigging angle of the antenna at the subterranean feed package focus of the beam waveguide (David Rochblatt, private communication, January 24, 2003).

c. Atmospheric Effects

The performance degradation at Ka-band due to the troposphere is expected not to significantly differ between 32 GHz and 37 GHz. The atmospheric contributions to noise temperature and attenuation are expected to be somewhat higher at 37 GHz but not by much. The contribution of the oxygen absorption coefficient (in dB/km) at 37 GHz lies below that of water vapor absorption at both frequencies (see Figure 1). However, the oxygen contribution to the atmosphere has a much longer scale height (about 5.4 km at zenith) than that of water vapor (about 1 km at zenith). The amount of water vapor absorption is, for all practical purposes, comparable at both frequencies as they both lie in the trough of the absorption curve (see Figure 1).

Atmospheric effects at Ka-band to be specifically researched include rain fades, scintillation and de-polarization due to rain and other particles. A significant program of studying atmospheric effects using water vapor radiometer (WVR) data has been conducted and comprehensive seasonal and monthly models have been developed for the purpose of characterizing both atmospheric attenuation and atmospheric noise temperature at the 32 GHz downlink frequency used by current and future robotic space missions [2].

Estimates of relative effects of signal attenuation at both 37 GHz and 32 GHz have been performed for the case of an antenna located at the Goldstone tracking site. It is assumed that the altitude of the ground station is 990-m above mean sea level, with an atmospheric pressure of 903 mB, an air temperature of 15 °C, and a relative humidity of 58%,

use of Ka-band is predicted to allow BPSK telemetry to be used for solar elongation angles down to 1 deg [6], and is planned to be demonstrated at 32 GHz using the Mars Reconnaissance Orbiter (MRO) spacecraft during its solar superior conjunction in October-November 2006. Given that the minimum solar elongation angle will reach 0.4 deg for this solar conjunction, simulated FSK (using tones) is also planned to be tested.

e. System Noise

Contributions o f system noise temperature due to antenna structure, amplifiers and follow-on equipment at 37 GHz are not expected to be too much different than at 32 GHz. Given the significant contribution of the atmosphere to the overall system noise temperature, extraordinary efforts to design low-noise amplifiers with very low noise temperatures is not warranted.

f. Space Loss

Assuming that both the transmit and receive elements of a telecommunications link utilize directional antennas, the combined effect of the λ^2 dependence in space loss with wavelength, and the λ^{-2} dependence of antenna gain with wavelength, results in a net λ^{-2} dependence of space loss with wavelength. As a result, for the same range distance, the space loss will be 1.3 dB less at 37 GHz than at 32 GHz. This assumes all other factors, such as pointing error, being equal.

g. Antenna Patterns

The antenna main-beam will be about 16% smaller at 37 GHz, than at 32 GHz. The pointing accuracy at 37.5 GHz requires careful treatment just as it does for designs at 32 GHz. For a 12-m diameter ground antenna (as planned as one element of large arrays of small antennas to be employed in the future DSN architecture), the half-power beamwidths are ~ 45 mdeg at 32 GHz and ~ 39 mdeg at 37 GHz. Roughly, 0.5 dB of power loss is expected for 10-mdeg pointing error with a 12-m diameter antenna. For significantly larger diameter antennas such as the 34-m diameter antennas of the DSN, maintaining stable pointing within the narrower beam at these high frequency bands requires good pointing models and techniques, such as monopulse pointing control.

4. Hardware Issues

As communication links are able to support much higher data rates, but within a confined spectrum, bandwidth efficient modulation techniques must be employed, which present new challenges for the 37 to 38 GHz Ka-band downlink allocations. Such techniques include multiple PSK and QAM schemes. Such existing hardware that possibly may be modified for 37 GHz for future generations include the 4th generation TDRSS User Transponder with Compatible Ku/Ka upconverter [7], and the Small Deep Space Transponder (SDST) used for deep-space applications

Specialized equipment, that will need to be built or modified to accommodate higher data rates at the 37-GHz frequency, include modulators such as a high data rate bandwidth efficient modulator [7]. Applied Physics Laboratory (APL) is developing a vector modulator intended for use at 32 GHz but could be extendable to support 37 GHz band [8]. Alternatively, the application of modulating an X-band signal followed by X4 multiplication is a viable method (Brian Cook, private communication, July 2004).

Digital-to-analog converters (DACs), such as those used for commercial video applications but are not space qualified, can support symbol rates of 200 Msym/s.

When modulation schemes such as multiple QAM and PSK are applied over the entire 1-GHz bandwidth, care must be taken to minimize out-of-band interference, within the

corresponding to a water vapor density of 7.45 gm/m^3. Scale heights of 5.4 km and 2 km are assumed for oxygen and water vapor, respectively (Steve Slobin, private communication, April 30, 2004). The results are summarized in Table 1, where "Tatm" denotes atmospheric noise temperature increase at both 90° (zenith) and 20° elevation angles

Table 1

Atmospheric Attenuation (dB) and Noise Temperature (K)

	Zen. Attn.	Zen. Attn.	Zen. Attn.	Zen. Attn.	Zen. Attn.	Zenith	20 deg	20 deg	20 deg	20 deg	20 deg	20 deg
Frequency	O2	H2O	Combined	Tatm O2	Tatm H2O	Tatm	O2	H2O	Combined	Tatm O2	Tatm H2O	Tatm
32 GHz	0.118	0.119	0.237	7.1	7.6	14	0.345	0.349	0.693	20.8	22.2	39.1
37 GHz	0.18	0.138	0.317	10.8	8.8	18.5	0.526	0.402	0.928	31.7	25.6	50.7

At 32 GHz, the contributions due to oxygen and water vapor are comparable. It should be noted that, depending upon conditions and site, these relative proportions can change. At 37 GHz, the attenuation due to oxygen exceeds that of water vapor. At 20° elevation angle, the magnitudes of the attenuation and noise temperature contributions are more revealing. Atmospheric attenuation runs about 0.93 dB at 37 GHz and about 0.69 dB at 32 GHz, which corresponds to 85% weather at Goldstone.

The effect on amplitude due to atmospheric scintillation at the Goldstone site can range from about 0.1 to 0.2 dB at low elevation angles [3].

The effects of liquid water and water vapor at 37 GHz were addressed for Space VLBI links by providing 10 dB of additional margin referenced at an antenna elevation angle of 10° under rainy conditions with a 2-mm/hour rainfall rate [4]. For deep-space links which operate at low margins, the effects of rainfall can be significant.

Link design for the DSN makes use of zenith attenuation and atmospheric noise temperature values, which are tabulated as a function of percent weather for all three NASA deep-space tracking complexes at Goldstone, Madrid and Canberra [2]. Strategies for mitigating weather effects on deep space Ka-band links are presented elsewhere [5].
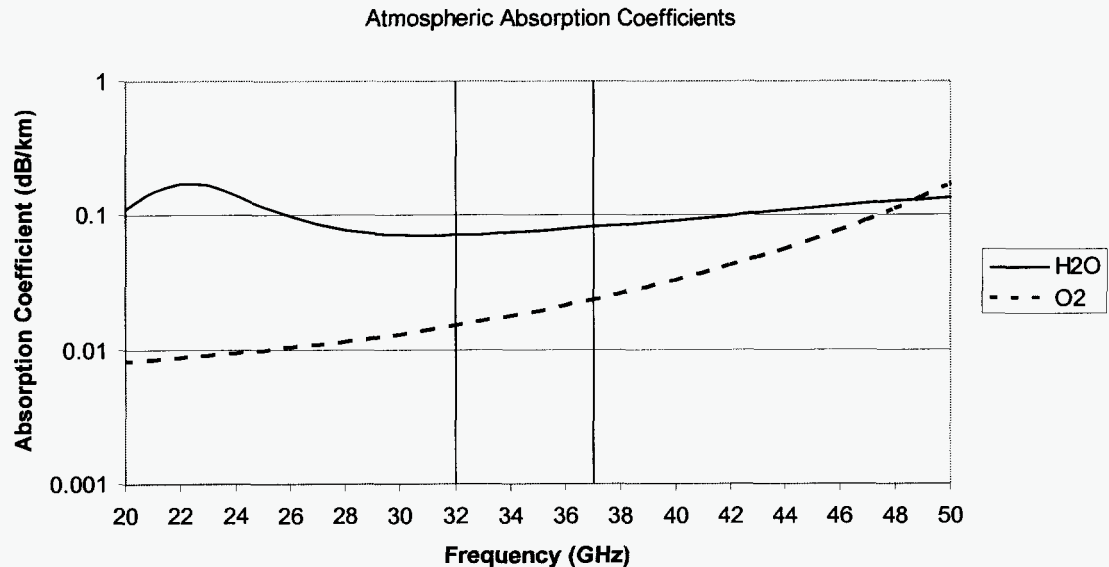
Atmospheric Absorption Coefficients

Figure 1 – Atmospheric Absorption Coefficients versus Frequency

d. Solar Charged-Particle Effects

Due to the dispersive nature of the solar coronal charged particles on signals, these degradation effects become less as the frequency increases. Thus, one expects performance at the higher 37 GHz frequency to be at least comparable but likely better than at 32 GHz. The

regulations set down by the National Telecommunications and Information Administration (NTIA). To meet such regulations, filtering is usually employed to reduce out-of-band emissions. Thus, additional hardware, required on highly bandwidth efficient systems, include specialized filters, such as a 3-pole Butterworth band-pass filter as one example [4].

The use of QAM with square-root-raised-cosine (SRRC) pulse shaping appears feasible for attaining the highest possible data rate in the 37-38 GHz band, but requires the use of linear power amplifiers. For Ka-band, such amplifiers (solid-state) are less than 30% efficient. For instance, a 0.5-W single stage power amplifier provides efficiencies in the 20% range. As more stages are combined for additional power output, the amplifier becomes less efficient, usually below 10%. However, there are now designs that employ spatial power combining of the output of hundreds of individual transistors situated in a grid on a single chip, resulting in additional total power output and added efficiency, such as Wavestream Corp.'s grid-array amplifiers at 31 GHz [9]. Such amplifiers could be extendable to 37 GHz and can operate either linearly or saturated.

Vector modulators and linear power amplifiers could support modulation schemes such as 16-QAM and 64-QAM for even greater bandwidth efficiency. Alternatively, GMSK can be used with amplifiers driven into saturation.

In the area of receivers, the Goddard/JPL-developed ASIC (first generation) is capable of acquiring, tracking, demodulating and detecting a BPSK symbol stream of up to 300 Msps. The ASIC is capable of demodulating and detecting BPSK, QPSK offset QPSK, and unbalanced QPSK among other I/Q schemes. 8-PSK can be handled through addition of FPGAs. The next generation ASIC is expected to accommodate a symbol rate up to 600 Msym/s and possibly higher, and is expected to incorporate 8-PSK and 16-QAM receiving algorithms. The high data-rate parallel digital receiver is discussed in [6]. A front-end processor capable of handling 1 Gbps TDM telemetry was developed in support of the NASA Ka-band Transition Program [10]. Various decoding schemes are supported by this processor.

In the area of coding, forward error correction codes are very important in terms of increasing power efficiency as well as spectral efficiency, especially in the area of deep-space communications which operate at low margins. Recent advances in the field have allowed systems to perform close to the Shannon limit. Such codes include Turbo codes and Low Density Parity Check (LDPC) codes. The Deep Space Network is not currently planning to use existing Viterbi or Turbo codes at the very high data rates anticipated for future mission scenarios. The current data rate limitation using Turbo codes in the DSN is about 1.6 Mbps. The DSN is currently studying the use of LDPC codes for symbol rates of up to about 100 Mbps (Ken Andrews, private communication, July 15, 2004). Examples of some work in the area of Turbo and LDPC decoding for commercial applications can be found in [11].

Antennas are not expected to be a major driving issue, as existing technology suffices. There are some development issues to make sure design is correct for that frequency, and one still needs to go through the same design iterations as one would do for 32 GHz. The costs should be similar to that of 32 GHz. The expected use of an array of small 12-m diameter antennas for the expected downlink signals on the ground-side should easily be optimized for use at 37 GHz, with minimal pointing loss, and maximized gain.

On the spacecraft side, a phased array antenna has been developed for use at 26 GHz by Harris Corp (Florida, USA) and was planned to be tested to determine effects of phased array signal distortions on BER performance for data rates up to 600 Mbps [6]. Such designs may be extendable up to 37 GHz.

5. LINK DESIGN AND DATA RETURN ISSUES

Potential future users of the 37 – 38 GHz frequency band include future Mars Network users, and lunar network users. In addition, several link designs for space-VLBI

(SVLBI) as a possible future user have been conducted. Other users of the band may include direct-to-Earth scenarios elsewhere in space, such as at the Sun-Earth L1 and L2 libration points.

a. Current Realizations

The 1-GHz wide bandwidth allocation between 37 GHz and 38 GHz allows for realization of very high data rates. We first survey the highest data rates currently transmitted or potentially transmitted over space links elsewhere in the Ka-band region. Ka-band data rates that are currently realizable include a 300 Mbps return link to the operational TDRS-8 (TDRS-H) spacecraft. There is also a current capability to receive up to 800 Mbps using a Single Access Return service link of the TDRS HIJ space-to-space satellites. This allocation uses a 650 MHz wide bandwidth where several modulation schemes (OQPSK, 8PSK, 8PSK/TCM, 16QAM, 16PSK and GMSK) were assessed for data rates between 600 Mbps and 1.5 Gbps [12]. It was determined that data rates in excess of 1 Gbps could be supported using 8PSK. If QPSK or GMSK are utilized, the channel should be capable of supporting data rates in excess of 800 Mbps. The study concluded that 8PSK provides the best performance, as it outperformed 16-QAM and performs well for data rates up to 1.5 Gbps [12]. Different error-correction coding schemes were also studied in combination with these modulation schemes.

b. Future Realizations: SVLBI

Some SVLBI missions have considered using the full 37 to 38 GHz downlink allocation in order to achieve the highest possible data rates. Designs using data rates of 4 Gbps and 8 Gbps have been proposed for possible future projects such as the Advanced Radio Interferometry between Space and Earth (ARISE) and International ARISE (iARISE).

The SVLBI proposed mission, VSOP2, proposed to use a 1.024 Gbps data rate with two orthogonal polarizations (RCP and LCP) each with 512 Mbps using QPSK waveforms in the Ka-band 37-38 GHz allocation [4]. The VSOP2 telecom design appears to be feasible during periods when there is no competition or conflicts for the allocated spectrum, such as from future lunar missions and Mars missions. The VSOP2 project ended in February 2002.

Data rates as high as 4.096 Gbps appeared feasible for SVLBI in the 37-38 GHz band, with some technical challenges to be addressed [4]. This scheme was suggested to be possible using both LCP and RCP polarizations with bandwidth compression modulation techniques, using 16-QAM and SRRC pulse shaping, although a feasible SRRC implementation for this data rate was not yet worked at the time of the study [4].

A baseline design for an 8 Gbps data-rate developed for ARISE assumed the frequency range spanning from 37 GHz to 39.5 GHz [13]. However, the 38 to 39.5 GHz portion of this bandwidth is not allocated for space research. Another study for ARISE, discussed a planned 8.192 Gbps data rate using 32-QAM, with dual polarizations, and the requirement for spectrally efficient filters (SRRC) to meet the FCC spectral allocation requirement [14].

Realistically, data rates of 8 Gbps or higher will likely require going to higher frequency bands such as W-band, as it would be a significant challenge to implement a workable digital QAM design to realize these high data rates in the 37 - 38 GHz allocation in the foreseeable future.

c. Future Realizations: Lunar and Mars Networks

Several possible link scenarios for future lunar and Mars communications links were presented by Noreen et. al. [15]. A set of inexpensive 12-m diameter ground antennas on Earth could provide nearly continuous coverage in the locale of a human base on the near-

side of the moon [15]. Each 12-m diameter antenna receiving at Ka-band could support Gbps data rates using nominal values of RF transmit parameters from the Moon [15]. For example, data rates that can be realized using a 37-GHz Ka-band data link from a 1-m diameter HGA and 10 W of RF radiated power to a 12-m diameter ground station are about 850 Mbps from the lunar surface (accounting for lunar brightness temperature) or about 3.2 Gbps from a lunar orbiting mission. Obviously bandwidth efficient modulation techniques will be required, or bandwidth allocation will limit data rates on the high side. Using a 12-m diameter antenna transmitting at 40 GHz in the forward link with 200 W of radiated power, will easily allow uplink of about 440 Mbps of data.

Mars communication links using 37 GHz may eventually realize very high data rates, especially as very large arrays of small diameter antennas are implemented on the Earth along with larger diameter antennas and higher power at Mars, either on an orbiting spacecraft or Martian ground base. The NASA Deep Space Network plans to augment its tracking network with large arrays of smaller diameter antennas along with implementing associated technology upgrades that could result in providing several times the effective receive capability of existing 70-m diameter antennas [15], thus greatly increasing the data return from Mars. For example, an array with receive capability 10 times greater than that of an existing 70-m station could receive 500 Mbps from a 3-m diameter antenna and a 1-kW K_a-band transmitter at Mars during maximum Earth-Mars range [15]. At closest Earth-Mars range, this link could, therefore, potentially support data rates of several Gbps, necessitating the implementation of bandwidth efficient modulation schemes discussed earlier.

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7. CONCLUSION

The use of the 37 to 38 GHz and 40 to 40.5 GHz frequency allocations of Ka-band is being considered for future space missions. This paper covered a wide variety of issues associated with the implementation and use of these frequency bands for deep space communications. The issues discussed included spectrum allocation usage with respect to these frequency bands, and expected performance advantages or degradations relative to 32 GHz deep space allocation. Also discussed was the state of the hardware developed (or proposed) for operating in this frequency band, especially from the standpoint of the prospects for achieving higher data rates that could be accommodated in the available bandwidth. Some potential users of this frequency band were identified as well as exploring some of their anticipated methods to achieve the potential high data rates.

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