Eavesdropping On Mars

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Abstract

The planet Mars has fascinated us for thousands of years but it is only during the development of our technology based age that our first tentative attempts in visiting the red planet became possible. The first flyby mission began with the USSR "Korabl4" launched in 1960. Unfortunately the vessel failed to leave our atmosphere but as we collectively gained experience in space exploration, subsequent missions enjoyed greater success. We currently have satellites orbiting Mars, relaying radio signals back to Earth. In addition, several mobile rovers explore the Martian surface.

The distance for radio communication are enormous and signals arriving on Earth are correspondingly weak. Compounding our potential for capturing crucial data on the Martian atmosphere, terrain and soil composition is the meager energy available, derived solely from solar radiation. In contrast to the the billion dollar installations that Governments deploy, can resource limited radio amateur enthusiasts intercept these radio transmissions from our cousin Mars?

This document examines the potential for a Martian eavesdrop. Although we may not have knowledge of specific error correction data codes that would enable message decoding, we can at least engage message detection. Further, we may be able to determine some modulation parameters associated with these recovered samples – for example the various signal bandwidths used and possible some indication of particular modulation formats applied.

This document is by its nature speculative. It represents a tutorial is radio communication system design that is directly translatable to terrestrial applications. The use of a Mars to Earth link scenario provides an interesting focus and illustrates many concepts and design procedures that will find practical application on Earth.

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1 Introduction

Early Mars exploration missions conducted by NASA took pictures of its surface as their space probes flew past the planet taking surface pictures and relaying data back to Earth (Mariner 3-4, 6-7). Subsequent missions orbited the planet in order to comprehensively map the Martian surface (Mars Odyssey, Mars Express and Mars Reconnaissance Orbiter).

Despite providing extensive surface data, planet landing is needed for soil composition analysis, atmospheric weather study, solar flux measurement and detailed surface topography mapping. To accomplish this, NASA has deployed two successful mobile rovers that have directly explored surface conditions (Opportunity and Curiosity). Since return flights would be unnecessarily expensive, data is transmitted back to Earth and collected by a network of geographically dispersed receiving stations. From Wikipedia [1] “In January 2004, the NASA twin Mars Exploration Rovers named *Spirit* (MER-A) and *Opportunity* (MER-B) landed on the surface of Mars. Both have met or exceeded all their targets. Among the most significant scientific returns has been conclusive evidence that liquid water existed at some time in the past at both landing sites”. This finding provides strong evidence that life may have once existed on Mars, based on our current terrestrial experience that consistently shows that where water exists, life follow.

The US Mars Science Laboratory launched in 2003 [1] deploys three exploration instruments that remain transmitting essential data even today

2003	Mars Express Orbiter/Beagle 2 Lander	ESA	Success/Failure	Orbiter imaging Mars in detail and lander lost on arrival
2003	Mars Exploration Rover - Spirit	US	Success	Operating lifetime of more than 15 times original warranty
2003	Mars Exploration Rover - Opportunity	US	Success	Operating lifetime of more than 15 times original warranty

The most recent US Mars Science Laboratory launched in 2011 [1] currently transmits data indicating the potential for future human colonization of the planet

2011	Mars Science Laboratory	US	Success	Exploring Mars' habitability

http://marsrovers.jpl.nasa.gov/mission/communications.html

NASA provides a dedicated Internet Website detailing all its Martian exploration initiatives

[3] http://mars.jpl.nasa.gov/

This Website provides information on the upcoming MAVEN mission [4] aimed at atmospheric data collection, scheduled for an opportune launch window between 18 November to 17 December 2013 and intended for Mars orbit insertion around 16 September 2014.

http://mars.nasa.gov/programmissions/missions/future/maven/

During its mission, microwave radio signals will be transmitted to Earth. Although NASA owns sophisticated high sensitivity reception capabilities covering many Earth based locations, it is conceivable that its transmissions may be detected by radio amateurs using moderate sized dish-antennae combined with suitable microwave reception equipment. A PDF fact-sheet on MAVEN is available at

http://lasp.colorado.edu/home/maven/files/2012/11/MAVEN-HQ_FactSheet.pdf

All exploration equipment sends data back to the Deep Space Network (DSN) [5]. The DSN employs three receiving stations located approximately 120 degrees apart on our planet, and using reception frequencies within the 26 cm (f = 1.15 GHz), 34 cm (f ~ 880 MHz) and 70 cm (f ~ 430 MHz) bands. However, less advertised, capability in the X-Band (7.0 ~ 11.2 GHz) should also exist.

http://deepspace.jpl.nasa.gov/dsn/

Transmissions in the X-Band (7.0 ~ 11.2 GHz) are also popular, used by the Mars Reconnaissance Orbiter, Mars Express, Mars Odyssey, Rosetta, New Horizon Pluto, Spitzer Space Telescope, Venus Express etc. The following Website describes one radio amateur's successful reception of signals from these traveling space vessels. FFT snap shots are included as well as details on the hardware developed for space message reception.

http://www.qsl.net/ct1dmk/dsn.html

Another radio amateur describes home-brew X Band receiver design here

http://www.kl7uw.com/DSN.htm

The next radio amateur pair (James Miller G3RUH and Freddy de Guchteneire ON6UG) demonstrate the use of a 1 meter 8.4 GHz dish antenna capturing signals from the “Venus Express / Mars Reconnaissance Orbiter Monitoring”. They report that the “The antenna on the space craft is 1.3m diameter, with an approximate gain of 41.23dBi, making the EIRP about 516Kw”. Presumably the space vessel transmitter supplies a respectable 38.87 Watts to its dish antenna! The following Website might be worth a visit

http://www.uhf-satcom.com/amateurdsn/vex/

Apparently radio amateur reception of space borne signals is alive and well!

2. Free Space Path Loss (FSPL) Calculation

2.1. Deriving The FSPL Equation Using A Minimum Of Mathematics

Although optical communications could provided significant advantages over conventional radio based links, this technology is still in its preliminary investigation phase. The "The Optical Payload for Lasercomm Science (OPALS), an optical technology demonstration experiment, could improve NASA's data rates for communications with future spacecraft by a factor of 10 to 100" [7].

http://scienceandtechnology.jpl.nasa.gov/

http://www.jpl.nasa.gov/news/news.php?CFID=ed801c9a-2161-4d6f-8d85-a4c977ecb822&CFTOKEN=0&release=2013-218

Articles on both antenna and radio propagation theory are prolific. However most, if not all, resort to complex mathematical derivations based on Maxwell's field equations, calculus and involved algebraic manipulations. It is inappropriate to repeat such a PhD level overkill here; instead simple geometric explanations are sufficiently adequate to explain Free Space Path Loss (FSPL) theory and in chapter 3, antenna "aperture area", especially in the context of dish antenna constructions.

To begin, we imagine a transmitter connected to a loss-less antenna that radiates equally in all directions (i.e. an "isotropic antenna"). We consider this antenna placed in a loss-less medium, for example the vacuum of space. All of the radio frequency energy delivered to this antenna emerges as radio frequency (RF) energy without loss. If we enclose the antenna with a spherical surface, then all the transmitted RF energy, collected over the total spherical surface will equal the energy delivered to the loss-less, isotropic antenna regardless of the radius of the sphere, or if the antenna is placed at the sphere's center or even if the surface is not a sphere, but continuous (without holes), or if the antenna is not isotropic but directional! However it is easiest to imagine a spherical surface with an isotropic transmitting antenna placed at its surface in order to develop a simple model.

It follows that the energy density will decrease as the sphere's radius d is increased, since the sphere's surface area A_s will increase as radius r increases according to high-school level geometry

$$A_s = 4 \times \pi \times d^2 \quad ...(1)$$

We now imagine a RF collecting surface with a circular opening. The area A_c of this circular opening depends on its radius r, or equivalently its diameter D according to

$$A_c = \pi \times r^2 \quad \text{where} \quad r = \frac{D}{2} \quad \text{so that} \quad A_c = \pi \times \frac{D^2}{4} \quad ...(2)$$

For example, the receiving antenna could be a 3-meter dish so that $D = 3$. It is quite reasonable to consider that the ratio of RF energy R "captured" by this circular aperture is simply the ratio between equation (2) and equation (1). By analogy, imagine a bottle left standing in a rainy day. It is certain that bottles with a wide opening will capture more rain. After dividing (2) by (1) we find that the gain ratio R becomes

$$R=\frac{\frac{\pi\times D^2}{4}}{4\times\pi\times d^2}=\frac{D^2}{16\times d^2}\quad ...(3)$$

It is common practice in RF engineering to use decibels rather than linear ratios when expressing energy relationships. Since equation (3) represents an energy ratio (i.e. a power ratio) we can express equation (3) alternatively as

$$R_{dB}=10\times\log\left(\frac{D^2}{16\times d^2}\right)=20\times\log\left(\frac{D}{4\times d}\right)\quad ...(4)$$

Using familiar logarithmic properties we will rewrite equation (4) in what will become a more convenient format

$$R_{dB}=20\times\log(D)-20\times\log(d)-20\times\log(4)\quad ...(5)$$

We see immediately that the ratio of energy collected R_{dB} increases as the RF Capture area D increases, but diminishes as the sphere's radius d increases (since this reduces energy density) and that an interesting constant $20\times\log(4)\approx 12.04$ dB is included. It is however standard convention to express energy ratios as a loss, rather than a captured energy ratio. To convert to Free Space Path Loss (FSPL), we simply change signs

$$FSPL_{dB}=20\times\log(4)+20\times\log(D)-20\times\log(d)\quad ...(6)$$

However not all receiving antenna use dish reflectors. For example, what if a lossless, isotropic antenna, identical to the transmit antenna was used. Again by convention, an isotropic antenna is assumed. The following equation is generally accepted to provide an adequate estimate for the equivalent “aperture area” A_i of a lossless, isotropic antenna operating at a wavelength λ.

$$A_i=\frac{\lambda^2}{4\times\pi}\quad ...(7)$$

We now apply exactly the same argument for “circular capture area” used to divide equation (2), (corresponding now to A_i) by the surface area of a sphere $A_s=4\times\pi\times d^2$ defined in equation (1). After some algebra we decide that

$$R=\frac{\lambda^2}{16\times\pi^2\times d^2}\quad ...(8)$$

Note that equation (8) looks quite similar to the previous equation (3)! However, before we convert to decibels, we will convert wavelength λ to frequency f using $\lambda=\frac{c}{f}$ where c represents the speed of light in m/s so that equation (8) becomes

$$R=\frac{c^2}{16\times\pi^2\times f^2\times d^2} \quad ...(9)$$

Converting to decibels and expressing energy ratio *R* as a *FSPL*

$$FSPL_{dB}=20\times\log(\frac{4\times\pi}{c})+20\times\log(f)+20\times\log(d) \quad ...(10)$$

The speed of light c is a defined quantity with an exact value of $c\equiv 299{,}792{,}458$ meters per second. The constant can now be substituted and equation (10) expressed with convenient accuracy to a fraction of a decibel

$$FSPL_{dB}\approx -147.6+20\times\log(f)+20\times\log(d) \quad ...(11)$$

Equation (11) now represents the familiar path loss equation expressed in standard SI units of Hz and meters. It is often convenient to modify the constant term when other units, such as MHz, GHz, km, or millions of km are used. To illustrate, using MHz and km as units, equation (11) can be modified as

$$FSPL_{dB}\approx -147.6+20\times\log(f\times 10^6)+20\times\log(d\times 10^3)$$

$$FSPL_{dB,\,MHz,\,km}\approx -147.6+120+60+20\times\log(f)+20\times\log(d)$$

$$FSPL_{dB,\,MHz,\,km}\approx 32.4+20\times\log(f)+20\times\log(d) \quad ...(12)$$

These new units are useful for terrestrial applications, but space communications may involve messages communicated over millions of km (i.e. Gm $d_{Gm}\equiv d\times 10^9$). Also frequency units of GHz may be preferred ($f_{GHz}\equiv f\times 10^9$). Using the same approach, equation (11) becomes

$$FSPL_{dB,\,GHz,\,Gm}\approx 212.4+20\times\log(f)+20\times\log(d) \quad ...(13)$$

At this stage we should recall that the FSPL equation is defined for isotropic antenna. These are fictitious items but provide a useful, independent benchmark to compare real antenna against. For example, a standard dipole antenna might present a power gain ~ 1.76 dBi where the “i” identifies power gain relative to an isotropic antenna. A multiple element Yagi antenna could provide a power gain of 10 ~ 15 dBi. These “improvements” are simply added to the “link budget” used to calculate overall link Signal To Noise (SNR) availability when transmit power, receiver noise figure, signal bandwidth, antenna gains and FSPL are taken into account. It would be folly to modify the FSPL equation based on some particular antenna design as such decisions are completely arbitrary whilst basing the FSPL equation on isotropic antenna presents no ambiguity or argument at all.

However there may be occasions where some confusion is encountered. Engineers required to compute radio link budgets will always insist on antenna gain specifications based on dBi since this is directly compatible with the FSPL equation. However, radio amateurs may prefer to know a prospective antenna gain performance relative to a familiar dipole that they might consider ready for replacement. For this, gain units in dBd, or gain relative to a dipole would be preferred.

Sometimes cynical opinion might suggest that antenna manufacturer's presenting antenna gain performance in dBi only do so to present a higher gain performance compared to units in dBd. It is difficult to find much credibility for this especially when units of dBi and dBd are well established in the industry! In general, the choice of gain units will probably reflect the needs of the end customer, as previously explained.

2.2 Free Space Path Loss Estimated Between Mars And Earth

Some interesting planet statistics are provided below in Table 1. The first statistic lists the average distance for Mars and Earth to the sun. Both planets have elliptical orbits. Exact inter-planet separation requires more detailed data but average data adequate to illustrate FSPL estimation methodology here.

Table 1 – Summary Statistics For Mars And Earth

	Mars	Earth
Average Distance from Sun	142 million miles	93 million miles
Average Speed in Orbiting Sun	14.5 miles per second	18.5 miles per second
Diameter	4,220 miles	7,926 miles
Tilt of Axis	25 degrees	23.5 degrees
Length of Year	687 Earth Days	365.25 Days
Length of Day	24 hours 37 minutes	23 hours 56 minutes
Gravity	.375 that of Earth	2.66 times that of Mars
Temperature	Average -81 degrees F	Average 57 degrees F
Atmosphere	mostly carbon dioxide some water vapor	nitrogen, oxygen, argon, others
# of Moons	2	1

Data was obtained from http://mars.jpl.nasa.gov/allaboutmars/extreme/quickfacts/. We observe that both planets have different year lengths (687 days, 365.25 days) so that both planets will align from time to time. If this occurs on the same side of the sun, the average interplanetary distance will become 142 – 93 million miles = 49 million miles. Alternatively, when aligned on opposite sides of the sun, the the average interplanetary distance will equal 235 million miles. To convert miles to km we need to divide by 0.62137. The closest average interplanetary separation will therefore equal ~78.9 million km or 78.9 Gm in the preferred units proposed here. Additionally, the maximum separation will be ~378.2 Gm. From this we can easily predict minimum and maximum FSPL for various communication frequencies (in GHz)

Table 2 – Free Space Path Loss Estimates Between Mars and Earth

Wavelength	Frequency	Min FSPL in dB	Max FSPL in dB	Comment
70 cm	0.43 GHz	243.0	256.6	DSN 230 foot Dish antenna
34 cm	0.88 GHz	249.2	262.8	Multiple DSN 35 meter HFA
26 cm	1.15 GHz	251.5	265.1	DSN 26 meter, orbiting craft
3 cm	7~11.2 GHz	270.3	283.9	X – Band – 10 GHz example

http://deepspace.jpl.nasa.gov/dsn/antennas/70m.html
http://deepspace.jpl.nasa.gov/dsn/antennas/34m.html
http://deepspace.jpl.nasa.gov/dsn/antennas/26m.html

Although the Deep Space Network (DSN) promotes its use of the 70 cm, 34 cm and 26 cm bands for public interest over the Internet. It has significant involvement in the X-Band as well. For example “Notable deep space probe programs that have employed X band communications include the Viking Mars landers; the Voyager missions to Jupiter, Saturn, and beyond; the Galileo Jupiter orbiter; the New Horizons mission to Pluto and the Kuiper belt, the Curiosity rover and the Cassini-Huygens Saturn orbiter”. Quote taken from

https://en.wikipedia.org/wiki/X_band

The X-Band is also used for radio amateur communications (10.0 ~ 10.5 GHz) with the upper frequency allocation used for satellite communication (10.45 ~ 10.50 GHz). According to the previous Wikipedia site, the “8/7” GHz sub segment is also used for uplink/downlink satellite communications.

X-Band reception is not beyond radio amateur reception capability and one local enthusiast (Bernie, ZL4IS) is well equipped for this band. A number of significant advantages are available for reception in this microwave band

- Very little X-Band activity (NZ) exists so the danger of interference is minimal
- Highly directional, high gain dish antennae allow accurate direction-of-arrival tests
- High directivity avoids unwanted signal contamination from solar noise
- Modern, inexpensive semiconductor devices provide low noise, high gain performance
- Standard FR-4 PCB substrate is feasible (Rogers Ceramic - Teflon Duroid is preferred)
- Frequency down-conversion to an intermediate frequency at 1,296 MHz is sensible

Each of the four bands offer specific advantages. Reception at 70 cm uses technologies already used for amateur use and Yagi antenna designs would be familiar to most enthusiasts. The FSPL reduces at lower frequencies, but high gain antenna design becomes problematic. Steering large Yagi structures towards a non-stationary Martian source could also represent a technical challenge and during maneuvers, maintaining rejection of solar noise could be difficult. Furthermore, the 70 cm band is highly populated, resulting in high possibility with interference.

The 23 cm band represents a convenient compromise. Relatively compact Yagi and parabolic dish antenna are practical and physical steering mechanisms would not require undue mechanical effort.

The FSPL will be higher than at 70 cm (increases by 6 dB for each doubling in frequency) but is offset to some extent as higher gain (dish) antenna are possible.

Finally, reception at X-Band frequencies is more technically challenging, but standard equipment is available and commercial dish antenna can be found and modified for specific frequency of operation. Also, designing a “home brew” frequency down converter PCB (or PCBs) is not inconceivable and inexpensive components, suitable to processing X-Band signals are available from suppliers such as Digikey NZ, Element 14 NZ etc.

Given that all bands have both virtue and drawbacks, none will be excluded in this document. The examples shown serve an educational purpose and the methodologies presented are generic. For example, designing a repeater link on the 2 meter amateur band will use the same design and planning procedures described here.

3. Microwave Dish Antenna Gain Estimates

The method for calculating the power gain of a parabolic dish antenna follows a similar argument to the one used for estimating FSPL. In short, the gain is equal to the ratio of dish input area compared to the antenna aperture area. To reuse the rain analogy, adding a funnel to a bottle will collect a lot more rain water than the original bottle would receive. The ratio increase will equal the funnel's input area divided by the mouth area of the bottle.

Repeating equation (2), the input area A_c of a circular dish antenna with diameter D is

$$A_c = \pi \times \frac{D^2}{4} \quad ...(14\ )$$

Also as previously indicated in equation (7), the aperture area A_i of an isotropic antenna is given by

$$A_i = \frac{\lambda^2}{4 \times \pi} \quad ...(15)$$

The dish antenna power gain must therefore be (14) divided by (15)

$$G = \frac{A_c}{A_i} = \pi^2 \times \frac{D^2}{\lambda^2} \quad ...(16)$$

This gain represents a “best case” estimate and assumes a perfectly accurate parabolic shape, required to focus all incoming parallel waves to focus at a single point. In practice, perfection is unobtainable and an “aperture efficiency” e_A fudge-factor is introduced to reflect this. Revising equation (16) now provides a more realistic gain estimate

$$G = e_A \times \pi^2 \times \frac{D^2}{\lambda^2} \quad ...(17)$$

Interestingly, the same equation' form is stated at http://en.wikipedia.org/wiki/Parabolic_antenna and suggests typical values for e_A between 0.55 and 0.7. As before, linear energy ratios are usually discouraged in favor of decibels so equation (17) will be better expressed as

$$G_{dB} = 20 \times \log\left(\frac{D}{\lambda}\right) + 20 \times \log(\pi) - E_A \quad ...(18)$$

This time “aperture efficiency” will be re-expressed as a loss term in dB ranging between 1.5 dB to 2.6 dB. Tidying up the constant term containing log(π) produces a final, more convenient expression for dish antenna gain

$$G_{dB} = 20 \times \log\left(\frac{D}{\lambda}\right) + 9.9 - E_A \quad ...(19)$$

Example1: Consider a moderately sized parabolic dish antenna with diameter D = 3 meter operating in the λ = 26 cm band. Assuming a mid range aperture efficiency (or better referred to now as an aperture loss) of 2 dB, its gain G_{dB}, relative to an isotropic antenna will be $G_{dB} \approx 29.1$ dBi.

Example2: Consider the moderately sized parabolic dish antenna used on the Venus Express / Mars Reconnaissance Orbiter referenced in the introduction. This uses a dish antenna with diameter D = 1.3 meter operating at 8.4 GHz. (λ = 3.57 cm). Since this dish is relatively small, we will assume an aperture loss of 0 dB. From this, its predicted gain G_{dB}, relative to an isotropic antenna will be $G_{dB} \approx 41.12$ dBi. Interestingly, the web page estimates the dish antenna' gain at 41.23 dB !

http://www.uhf-satcom.com/amateurdsn/vex/

8419.074074 DSN Channel 17

4. Mars to Earth Link Budget Predictions

4.1. Link Budget Objectives

A communication link consists of a signal transmitting source, a channel that carries information and a receiver that recovers original information. The channel will introduce a variety of aberrations that will introduce errors. These include additive noise, bandwidth truncation, frequency response distortion, amplitude non-linearity, interference from other co-located transmitting sources and so on. The link objective is to recover the original information despite imperfections in the channel.

Channel perfection is not essential however and receiving systems are tolerant of channel aberrations up to a certain extent. The methods used to encode the required information and then decode in the receiver determine the degree of channel tolerance available. For example, low bandwidth systems will be more tolerant of additive noise in the channel than wider band systems. However this strategy may not improve tolerance to similar modulations co-located in the same spectrum used. Other methods may be used however – for example a simple Binary Phase Shift Keying (BPSK) modulation format will be more tolerant to channel distortions than a higher modulation scheme such as Quadrature Amplitude Modulation (QAM). Even so, some residual demodulation errors may remain.

In some cases, a particular application may be resilient whilst other application could demand a much higher standard in data quality. For example, an application that encodes data in a TV remote control would consider that a few data errors would be unimportant but an application involving accurate financial transfers would find that errors in the amounts sent and received would be highly problematic. In these cases, many error correction schemes are added “on top” of the underlying modulation methods. The simplest would be to repeat a message several times to ensure that each reception is identical, otherwise all are discarded. Other methods test for some structure embedded in the data, such as a “parity check” or “sum check”. In more advanced systems, message structures employ complex encoding schemes that increase reliability.

In most cases the channel is uncontrolled but the transmitter and receiver system has free variables. For example, many channel imperfections, such as additive noise, can be compensated for simply by increasing transmitted power. A given system will typically define a minimum Signal To Noise (SNR) required for adequate performance. It is pragmatic to ensure that an adequate SNR excess is available so that unexpected channel variations will still be accommodated. When designing a communication system, a “link budget” calculation is required. This calculation determines minimum transmitted power requirements and sets a sensible margin above this limit based on expected channel variation.

The space channel is benign compared to many terrestrial versions and the most significant imperfection is FSPL. Additional imperfections include excess noise introduced internally at the receiver, thermal noise generated in the receiving antenna, solar noise and noise from background microwave radiation. To mitigate these imperfections, the system designer has control over a reasonable number of system parameters

- System Bandwidth
- Transmit Antenna Power Gain
- Receive Antenna Power Gain
- Transmit Power
- Data Encoding and Error Correction Method

4.2. Estimating Solar Energy Available For Transmission

We will develop hypothetical link budgets based on a scenario where a radio amateur attempts to eavesdrop on a Martian transmission intended to send data back to earth. Unlike the large budget professional communication networks, the amateur's resources will be limited. Even so, could message detection, if not message decoding even be possible?

To test the plausibility of this scenario we need to introduce some assumptions based on “best guess” hypothesis'. Although NASA etc. provide excellent pictures of the Martian atmosphere and its surface, the amateur may also be interested in gaining access to the raw radio signals directed at Earth. This is a one-way link – no possibility of transmitting back is entertained here!

The examples presented are generic. Once the principles are grasped, application to terrestrial applications is straightforward. For example, link budget analysis is well suited to Windows Excel spreadsheets (or LibreOffice Calc in Linux) any can be applied to FM repeater link design at VHF (144-148 MHz) or UHF (430-440 MHz). Although numbers change, the same link variables remain.

To begin, we need to make an assumption on the available transmitted power from a Martian source. This could come from an orbiting satellite or a ground exploration rover. WE will assume that in both cases, all energy used comes from a solar source (as opposed to a nuclear battery).

On Earth, the “best cases” sunlight energy falling on its surface is S = 1,366 watts per square meter providing the sun is overhead on a cloudless day. For more information, why not visit this link

http://en.wikipedia.org/wiki/Earth%27s_energy_budget

How much solar energy will be available on Mars? From Table 1

	Mars	Earth
Average Distance from Sun	142 million miles	93 million miles

Light energy (and radio frequency energy) obeys a “square law” relationship with distance. For example, each time distance *d* doubles, energy reduces by a factor of four. We can immediately see

$$S_M = S_E \times \left(\frac{d_E}{d_M}\right)^2 = 1366 \times \left(\frac{93}{142}\right)^2 = 586 \quad ...(20)$$

in Watts per square meter (i.e. S_M = 586 Wm^{-2}). Unlike Earth, we can expect the Martian sky to be largely cloud-free but some dust storms will occur from time to time and partly obscure solar radiation. However, like Earth, Mars also rotates but with a cycle of 24 hours 37 minutes so that ground stations will only receive solar energy ~50% per cycle. Orbiting satellites would not be as affected and could adopt an orbit that receives continuous solar illumination. We can however expect that ground stations would employ directional solar panels that would adjust automatically to receive the maximum available solar energy.

Exploration rovers would report to a relatively large fixed base installation. Perhaps this could be similar to a truck or bus but in future missions, ground stations could resemble a small township. However, based on current missions, sufficient area would be available to mount several solar panels, perhaps each having a collection area ~2 square meters.

The light to electricity energy conversion for current solar panels is not spectacular and values as dismal as 5 % are not uncommon. However, given the massive financial budget available to an Earth to Mars exploratory mission, skimping on Dick Smith or Jaycar solar panel offerings seems unlikely. Further, many optical devices perform better at low temperatures and the low ambient exposure on a Martian surface at ~ -81 F (-63 C) is probably benign. Given this, a conversion efficiency of ~15 % should not be unrealistic.

Therefore we will make the following hypothesis, based on a moderate sized fixed base installation with four 2 m^2 solar panels operating at 15 % light to electricity conversion efficiency

Maximum Solar Energy Density	586	Watts / m^2
Solar Panel Light Capture Area	2	m^2
Number Of Solar Panels	4	
Solar Panel Conversion Efficiency	15	%
→ Best Case Energy Capture =	703.2	Watts

However we need to consider an average energy harvest, based on the Martian day to night cycle, potential obscuration from dust storms (or even from the passage of either of its two moons), storage battery charge to energy retrieval efficiency and potential efficiency decay due to aging over time.

Best Case Energy Harvest	703.2	Watts
Martian Day To Night Availability	50	%
Free From Obscuration Availability	90	%
Battery Energy Retrieval Efficiency	90	%
End Of Mission Life Availability	90	%
→ Average Energy Harvest Available =	256.3	Watts

From this scenario the energy availability is meager. Further, only a percentage of this could be used to power communication equipment as other base systems will also demand power supplies. For example, at least one computer will be essential to orchestrate general operation and an ever-ready back-up CPU will be essential to prevent avoidable mission failure. In addition, significant data processing, formatting, storage, retrieval and error checking will represent tasks demanding indefatigable attention. Both antenna and solar panels will require motorized mounts to maintain optimal positions. And then keeping tabs on those meandering rovers will require continuous supervision.

In order to circumvent these limitations, full time transmission from Mars to Earth would be inappropriate. In any case, planet rotation would prevent this anyway. A pragmatic approach could be to store measurement data over each Martian day (or days) and then send the payload in one opportune transmission burst. For example, a given burst might only last a few hours, relative to a rotation cycle of 24 hours 37 minutes. The average to burst energy ratio requirement would therefore be ~0.12 (i.e. 12 %).

Based on these general considerations, we will assume each transmit burst might operate at (say) 10 Watts output power. It is probably that non constant envelop modulation formats would be used as opposed to constant envelop FSK formats. These offer higher data throughput to bandwidth efficiency, but require linear RF power amplification. Based on typical terrestrial based linear power amplifier efficiency, we will assume similar DC to RF power conversion efficiency of ~ 30 %. The RF components of the transmitter system will possibly consume ~33.33 Watts per burst. On average, this would suggest an average power drain of 4.0 Watts, based on a 12 % duty cycle. Compared to the available 256.3 Watts of average energy harvested, this energy demand would only represent ~1.56 % of the available energy budget. Given that this demand does not seem unreasonable and that transmission bursts, each day, are not mandatory, our “first guess” that the transmitted power would be ~10 Watts per burst seems quite realistic.

4.3. Hypothetical Link Budget Estimations

We will consider two link scenarios; S1 will operate on the 26 cm band (1,150 MHz) and S2 will operate on the X-Band. For the purpose of illustration, a 10 GHz carrier will be proposed (although frequencies ~8.4 GHz are more probable). Both scenarios will transmit at P_{Tx} = 10 Watts but have differing bandwidths (BW). However, what range of BW would these Martian transmissions use?

In part answer, one NASA 160px x 120px image download weighed in at 7.9 KB (8,093 bytes)

http://mars.nasa.gov/images/MarsOceanRiverDeltaComparison-thm.jpg

If transmitted at 1 bit/second, this would have taken 8,093 seconds to download (2.25 hours!). During this time-frame, it seems reasonable that a mobile rover would have ample time to garnish many additional picture images! Perhaps a rover would be easily capable of capturing thousands of images but would these be significantly different and therefore worthy of transmission? It is unlikely that a ground based rover would move at breakneck speed but a more leisurely pace seems realistic. To use a familiar context, an average person might stroll comfortably at about 1 m s^{-1}. Perhaps a Martian rover would traverse its Martian terrain at a similar pace? Also, how often does scenery change with distance? On Earth, it seems improbable that any major new structures would appear every 10 meters or so. However, after walking about 100 meters, we might find another street block, perhaps some traffic lights and so on. Although not to suggest the danger of Martian “speed cops” it could be reasonable to expect that something of interest might be useful to send back to base every 100 seconds or so.

If so, transmitting this 8,093 bytes in 100 seconds would require a data transfer rate of 80.93 bytes per second. However 1 byte = 8 bits based on standard engineering definitions. This suggests a data capacity of 647.44 bits per second!

If simple BPSK modulation is used at 1 bits / Hz, then a channel BW from the rover to base would need to be 647.44 Hz. However some overhead would be needed for error correction algorithms to operate. It is common practice to use 2:1 coding, although sometimes 3:1 coding could be used. Given 2:1 coding, the required channel BW would need to be 1,295 Hz or greater. If the base were to transmit each new snapshot to Earth, it would need to adopt a similar BW. It could however adopt a higher modulation format in order to operate at lower bandwidth, but this would require a correspondingly higher Signal To Noise Ratio (SNR) in this reduced bandwidth. Although terrestrial communication links are bandwidth limited due to regulatory restrictions, Mars to Earth communications do not suffer such artificial limitations. It would be optional to choose BPSK, QPSK, QAM16, QAM64, QAM256 etc. If QAM256 modulation was selected (on some particular occasion) then 8 bits per Hz capacity would be possible. This would reduce the channel bandwidth from 1,295 Hz to 162 Hz.

Obviously these scenarios are speculative. However we can propose a “best guess” range of BW to choose from when searching for signals emanating from Mars. These could reasonable range from ~100 Hz to several kHz. It may be a good bet to expand this range to ~10 Hz to ~10 kHz. This represents the most probable BW range based on our assumptions and the consequence of “getting it wrong” is inconvenient, perhaps, at worst and interesting at best. Certainly, for the purpose of demonstrating how a link budget is calculated, this target range is perfectly suited!

Interim Summary

Transmit Power	10.0	Watts
Minimum FSPL @ 26 cm	251.5	dB
Maximum FSPL @ 26 cm	265.1	dB
Minimum FSPL @ 3 cm	270.3	dB
Maximum FSPL @ 3 cm	283.9	dB
Minimum Channel BW	10	Hz
Maximum Channel BW	10	kHz

We will now consider antenna parameters. Given that we allowed 2 m^2 per solar panel on the base (4 panels → 8 m^2 total), then by the same token, allocating space for a 3 meter diameter dish (7.07 m^2) represents similar importance. Using equation (19) with $E_A = 2$ dB for the 26 cm band.

$$G_{dB,\,26\mathrm{cm}} = 20\times\log(\frac{D}{\lambda})+9.9-E_A = 20\times\log(\frac{3}{0.26})+7.9 = 29.1 \quad ...(21)$$

There would be little reason to implement a different diameter dish for the 3 cm band. However the aperture efficiency could be lower due to parabolic curve inaccuracies. We will assume E_A = 4 dB for the 3 cm band. The predicted dish antenna gain will be

$$G_{dB,\,3\mathrm{cm}} = 20\times\log(\frac{3}{0.03})+5.9 = 45.9 \quad ...(22)$$

Will a typical radio amateur interested in intercepting Mars to Earth transmissions be able to procure a 3 meter dish or provide suitable mechanical mounts with motorized directional adjustment? We will assume that a more limited budget would be available. Perhaps a 1 meter dish antenna would be more practical? We will assume this dimension.

The radio amateur dish will use D = 1 meter in this example for 26 cm or 3 cm operation. Smaller dishes will presumably have higher aperture efficiency than large diameter versions. However the surface accuracy might be somewhat inferior to a highly machined component available of an interplanetary exploration budget. We will assume E_A = 4 dB in both cases.

Given these assumptions the radio amateur's antenna gains will be

$$G_{dB,\,26\mathrm{cm}} = 20\times\log(\frac{1}{0.26})+5.9 = 17.6 \quad ...(23)$$

$$G_{dB,\,3\mathrm{cm}} = 20\times\log(\frac{1}{0.03})+5.9 = 36.4 \quad ...(24)$$

We can now complete our link budget

S1 Link Budget Summary (26 cm)

Transmit Power	+40	dBm (10.0 Watts)
Transmit Antenna Gain	29.1	dB
Receive Antenna Gain	17.6	dB
Minimum FSPL @ 26 cm	251.5	dB
→ Maximum Signal Level	**-164.8**	**dBm**
Maximum FSPL @ 26 cm	265.1	dB
→ Minimum Signal Level	**-178.4**	**dBm**

S2 Link Budget Summary (3 cm)

Transmit Power	+40	dBm (10.0 Watts)
Transmit Antenna Gain	45.9	dB
Receive Antenna Gain	36.4	dB
Minimum FSPL @ 3 cm	270.3	dB
→ Maximum Signal Level	**-148.0**	**dBm**
Maximum FSPL @ 3 cm	283.9	dB
→ Minimum Signal Level	**-161.6**	**dBm**

Note: Although the FSPL at 3 cm is much higher than at 26 cm, this would be compensated for by using one directional antenna only. However this system uses two directional antenna, so that the increased path loss is not only compensated but greatly reduced!

Relative to familiar FM VHF and UHF communications, these signal levels would appear to be unusably low in comparison with typical receiver sensitivity limits (e.g. -119 dBm for 12 dB SINAD). However it is necessary to consider that a typical “narrow band” FM receiver will have an IF BW ~15 kHz, corresponding to 25 kHz channel spacing with some “guard band”. Also, our primary ambition is signal detection, not signal decoding. Even for high received signal levels, message decoding would require accurate knowledge of the exact modulation parameters and and code or codes used for data encoding and error correction schemes.

A better “metric” is to compare received signal noise to thermal noise. Since a typical radio amateur probably won't have access to liquid helium cooled antenna dish and amplifying components, we will use thermal noise power exhibited by conductors at room temperature as a baseline. Expressed in dBm, the value is ~ -174 dBm, measured in a 1 Hz bandwidth. This power quantity will increase by 10 dB for each decade increase in bandwidth

BW = 1 Hz → P_n ~ -174 dBm

BW = 10 Hz → P_n ~ -164 dBm

BW = 100 Hz → P_n ~ -154 dBm

BW = 1 kHz → P_n ~ -144 dBm

BW = 10 kHz → P_n ~ -134 dBm

The best signal strength in S2 is -148.0 dBm. These signals should be detectable providing their transmitted bandwidth is less than a few kHz. Modern low noise amplifiers (LNA) can easily offer noise figures below 0.5 dB and suitable devices are available for a few $NZ. The receiver noise contribution can be assumed to be negligible. Also, modern signal processing techniques can reveal signals below the noise floor. For example, the Fast Fourier Transform (FFT) available on many spectrum analyzers and PC/notebook sound-card software (virtual) oscilloscopes almost universally offer FFT processing. In addition, spectral averaging (after the FFT) has great potential to reveal various received structures that could otherwise go unnoticed.

Radio amateur enthusiast therefore have many tools in their arsenal to aid such lofty ambitions as eavesdropping on signals from Mars. Significant gains can be had by using larger diameter dish antenna. In addition, multiple dish antenna can be used. These can be combined, increasing aperture area. This combining does not need to occur at the carrier frequency (e.g. 3 cm); instead signal combining at the output of multiple receivers is equivalent and may be more practical. Combining after FFT analysis may also be practical and could provide immunity to inter-channel phase errors.

5. Concluding Remarks

Although the distances involved in a Mars to Earth communication link are enormous, even resource limited radio amateurs may be able to intercept messages directed to Earth from exploratory Martian craft. The signals will be correspondingly weak and in comparison with conventional VHF and UHF radio communications, perhaps undetectable. However several trump cards reside in our arsenals – the use of moderate sized parabolic dish antenna offer significant signal capture capability compared to much lower gain (but familiar) dipole and Yagi antenna. Further, specialized receiving equipment can offer much lower system noise than conventional FM transceivers intended for terrestrial use. Although not discussed here, this equipment generally adopts a receiver Noise Figure (NF) between 7 dB ~ 10 dB, necessitated as a compromise between adequate weak signal resolution and strong signal overload resilience. In contrast, space signal receiver suffer little danger from overload as they reside in minimally populated, extremely weak signal environments. The primary interferes are solar noise, sky noise and “false detects” from spurious signals leaking from conventional terrestrial equipment operating on other frequencies.

The primary intention of this document is to provide an interesting tutorial on radio communication system design against a background of a semi-science fiction planet exploration scenario. Early writings such as “The War Of The Worlds” (H. G. Wells), “The Martian Chronicles” (Ray Bradbury) and the science fiction film “Invaders from Mars” (1953) all testify to our fascination with our red planet cousin. In fact, so compelling has been our belief in extraterrestrial life that when “The War Of The Worlds” was broadcast as an American radio program on October 30, 1938 as a Halloween stunt, mass public panic ensued!

http://en.wikipedia.org/wiki/The_War_of_the_Worlds_%28radio_drama%29

http://www.youtube.com/watch?v=Ury5b-qtI1Y

Following from ancient Roman mythology, Mars, “the God of War” inspired our predecessors. In 1877, the Italian astronomer Giovanni Schiaparelli described “canals” observed through telescope observation. Although later revealed as an “optical illusion”, we seem to engage a natural enthusiasm on questions regarding “life elsewhere”. Of all the planets inhabiting our solar system, Mars seems most likely to support life; the existence of surface water being our best sought evidence for the potential of life there. Finding either past remnants or current indicator of life activity has always been our ambition. All Martian exploratory missions have embraced this aim.

Today's science fiction becomes embraced by science fact. Radio signals continually emanate from a Martian source. Can we intercept these signals? What apparatus would we need. Would this be feasible within a typical radio amateur's finance-limited budget? This document presents a possibility of such engagements in what could arguably be described as one of our most noble human endeavors.

6. Appendix

6.1. Internet Websites Referenced In This Document

The following Websites provide interesting information of past, current and future planned exploratory missions to Mars.

6.1.1. Progress From Current NASA Rovers On Mars

Although Wikipedia receives criticism for accuracy and completeness, it does provide a useful "first stop" portal into many areas requiring informational research. The degree of comprehensiveness does vary, but Wikipedia clearly indicates where its external submissions are deficient in clarity, editing requests are made appropriately and required referencing citations are made for each unsupported claim made by its Authors. It is, as in any publication, the reader's responsibility to assess the credibility and authenticity of information presented. In this context, the consequence of any informational errors, is these exist, is probably immaterial.

The following Website provides a clear and comprehensive account of many Martian exploratory missions

[1] https://en.wikipedia.org/wiki/Exploration_of_Mars

7.1.2. Current International Mars Exploration Initiatives

The following Website tabulates a historical list of Martian exploration missions beginning with an unfortunate premature launch failure by Korabl 4 in 1960 and ending with the currently successful Mars Science Laboratory landing launched in 2011.

1960	Korabl 4	USSR (flyby)	Failure	Didn't reach Earth orbit
2011	Mars Science Laboratory	US	Success	Exploring Mars' habitability

[2] http://mars.nasa.gov/programmissions/missions/log/

6.1.3. NASA Internet Website Detailing Mars Exploratory Missions

This Website provides interesting information suitable for a general audience

[3] http://mars.jpl.nasa.gov/

6.1.4. MAVEN Atmospheric Analysis

MAVEN has the following deployment schedule

Launch Window:	18 November to 7 December 2013
Mars Orbit Insertion:	~ 16 September 2014

[4] http://mars.nasa.gov/programmissions/missions/future/maven/

6.1.5. Communication Frequencies and Data Rates

Information on the Deep Space Network (DSN) can be found at

[5] http://deepspace.jpl.nasa.gov/dsn/

Mars to Earth data transfer rates vary from 500 bits / second to 32,000 bits per second although Earth to Mars transmission rates can be as high as 2 MB/s.

http://mars.jpl.nasa.gov/msl/mission/communicationwithearth/data/

Shorter wavelength communications are also used. For example,

6.1.6. NASA Quick-Facts on Mars

[6] http://mars.jpl.nasa.gov/allaboutmars/extreme/quickfacts/

6.1.7. Future Optical Communication Technology

The use of laser communication technologies provides significant potential for highly directional communication links between space and Earth. Unlike conventional radio-wave based communication links, transmitted energy remains tightly contained in a narrow beam, significantly reducing energy loss. In addition, unwanted interference from terrestrial sources is far less probable as only signals within narrow laser-based beams will be detected.

[7] http://scienceandtechnology.jpl.nasa.gov/

http://www.jpl.nasa.gov/news/news.php?CFID=ed801c9a-2161-4d6f-8d85-a4c977ecb822&CFTOKEN=0&release=2013-218

6.1.8. Future Martian Missions

The ExoMars Orbiter launch plan in January 2016 represents a series of mission intended to indicate if life had ever existed on Mars. It includes a satellite “Electra” that will also act as a relay station between ground based rovers and Earth.

http://mars.nasa.gov/programmissions/missions/future/exomarsorbiter2016/

The ExoMars Rover launch is scheduled for 2018. It will contain a sophisticated Mars Organic Molecule Analyzer (MOMA) that will search for molecular byproducts of previous life.

http://mars.nasa.gov/programmissions/missions/future/exomarsrover2018/

NASA plans further missions in 2020 involving an advanced robotic rover. This may possibly rely on many anticipated advanced in artificial intelligence.

http://mars.nasa.gov/programmissions/missions/future/m2020/

http://mars.jpl.nasa.gov/news/whatsnew/index.cfm?FuseAction=ShowNews&NewsID=1401

Judging from the foresight and commitment shown by NASA in its Mars exploration program, it is reasonable to forecast eventual colonization of our fellow planet. Science fiction is waiting on our doorstep! We are moving to the door, when will we open it in greeting?

6.2. Additional Analysis – Antenna Apertures

Where did the “aperture area” in equation (7) come from?

$$A_i = \frac{\lambda^2}{4 \times \pi} \quad ...(25)$$

Unfortunately most, if not all articles on the subject resort to PhD level mathematics involving an allegiance to “Maxwell's electrodynamic equations”, complex algebra, advanced calculus and excessively expensive computer simulation software. This is not such a document nor is its audience expected to consist of gifted mathematicians. Instead it presents common sense, down to earth explanations that the general public can access.

Consequently, a conventional IEEE writing style is avoided and the use of “colloquial” terms and references are eminently appropriate. The document is intended for a general audience but focuses on the radio amateur community, people who work in radio telecommunication fields and those just interested in a super-science fiction read.

To return to the question, where did equation (7) come from. To recall, this had been derived by others based on the use of a lossless, omni-directional “isotropic radiator”. Presumably this radiator was selected to simplify mathematical analysis due to its inherent 3-axis (spherical) symmetry. Once its radio frequency energy is released, equal energy density inhabits the surface of a sphere, emanating from its (point) source and expanding radially at the speed of light *c*. Although this provides a useful structure for benchmarking the performance of other real-world antenna configurations, we will not consider it here. Instead we will consider the humble dipole antenna!

To begin, we will assume that the dipole radiate energy at equal density from all elements along its length, although we know that the majority of radiation occurs from its center were current flow is maximum. We can reasonably hypothesize that the radiation will come from a circular aperture with a diameter equal to λ / 2 i.e. a radius of λ / 4. Since we know that the area A_c of a circle of radius r is $A_c=\pi\times r^2$ it follows that $A_c=\pi\times(\frac{\lambda^2}{16})$. Let us consider that A_c, for now, represents the aperture area for a dipole antenna. The Adjusted Free Space Path Loss (*AFPSL*) of this antenna, as before, equals the ratio between the total energy available on the surface of a sphere with radius *d* (on which it resides) and is capture area. Since the surface area of a sphere A_s is known to be $A_s=4\times\pi\times d^2$. Note that we still assume an isotropic source, but consider a dipole receiving antenna. As before the ratio R_{adj} of captured energy to that available is just the ratio of A_c to A_s i.e.

$$R_{adj}=\frac{A_c}{A_s}=\frac{\pi\times(\frac{\lambda^2}{16})}{4\times\pi\times(d^2)}=\frac{(\lambda^2)}{64\times(d^2)} \quad ...(26)$$

How does this adjusted, energy capture ratio compare to that predicted from an isotropic receiving antenna? As before, we simply consider a ratio *k* between R_{adj} and the previous equation (8).

$$k=\frac{\frac{(\lambda^2)}{64\times(d^2)}}{\frac{\lambda^2}{16\times\pi^2\times d^2}}=\frac{\pi^2}{4} \quad ...(27)$$

We can express this power ratio k as an increase of receiving gain of a dipole antenna (based on our known false assumption) as a dipole gain G_d

$$G_d = 10 \times \log\left(\frac{\pi^2}{4}\right) \simeq 3.92 \quad ...(28)$$

The dipole antenna gain is often quoted as 1.76 dBi. Equation (28) predicts a slightly higher gain of ~2.1 dB. However it assumes an equal current distribution along the dipole element's length when most of the current density is known to concentrate towards its center (the current at its ends must equal circuit as this represents an “open circuit”). Therefore equation (28) overestimates the dipole antenna's aperture area, resulting in an elevated gain estimate. The derivation does however illustrate basic physics relating to electromagnetic theory. In addition, the mathematics employed are no more advanced than would be expected from an early high school education. In any case, when considering communication between a distant planet millions of miles away, of what significance is a decibel or two?