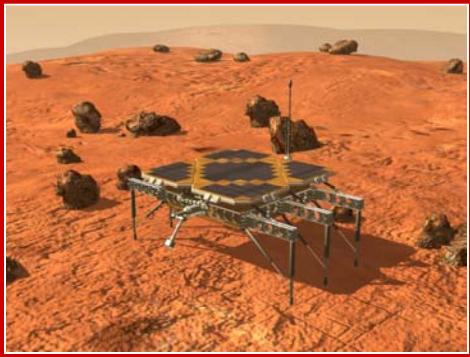
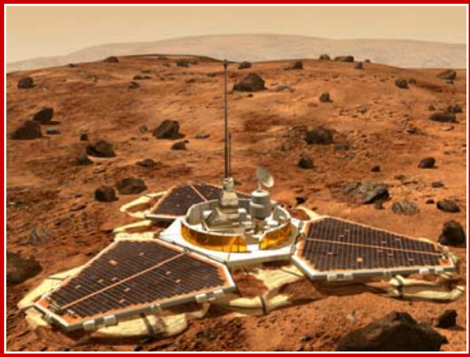
Networks on the Edge of Forever:

Meteor Burst (MB) Communication Networks on Mars

Version 1.0





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i. LIST OF ACRONYMS

ATIES	Abbreviated Technology Identification, Evaluation, and Selection
AU	Astronomical Unit
CA	Contributing Analysis
CDE	Collaborative Design Environment
DSM	Design Structure Matrix
DSN	Deep Space Network
EDL	Entry, Descent, and Landing
EOL	End Of Life
ESA	European Space Agency
ISCU	In-Situ Communication Utilization (ISCU)
kbps	kilo-bits-per-second
LPI	Lunar and Planetary Institute
MB	Meteor Burst
MCC	Meteor Communications Corporation
MGS	Mars Global Surveyor
MR	Mass Ratio
MRS	Mars Relay Satellite
MS	Master Station
NIAC	NASA Institute for Advanced Concepts
NOEF	Networks On the Edge of Forever
PI	Principal Investigator
PV	Photovoltaic
RF	Radio Frequency
ROSETTA	Reduced Order Simulation for Evaluation of Technologies and Transportation Architectures
RS	Remote Station
SEI	SpaceWorks Engineering, Inc.
TDM	Time-Division-Multiplex
UHF	Ultra High Frequency
USRA	Universities Space Research Association
VHF	Very High Frequency

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ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The envisioned future may include continuous operating outposts and networks on other worlds supporting human and robotic exploration. Given this possibility, a feasibility analysis is proposed for a communications architecture based upon reflection of ion trails from meteors in planetary atmospheres. Such Meteor Burst (MB) communication systems consist of semi-continuous, low bandwidth networks possessing both long distance capability (hundred of kilometers) and lower susceptibility to atmospheric perturbations. Meteor Communications Corporation (MCC) and its personnel (developers and patent holders of commercial terrestrial MB systems) are associated as technical partners for this examination. A proposed architecture on the Martian surface is presented. In order to facilitate global communication, various high power nodes are scattered throughout the planet. These act as nerve centers that can communicate either directly with Earth or relay information to orbiting satellites. Remote terminals can be placed on various systems: autonomous robots, weather stations, human transport craft, and crewed bases.

CHAPTER 1: INTRODUCTION

MOTIVATION

"There will be hundreds of millions of PCs in the world, but billions of other Net access devices. Coming right behind that, perhaps trillions of "things" we'd never call computers…All of them will be outfitted with the ability to communicate, and with specialized, energy-efficient, inexpensive chips-which are a very different animal altogether than the brains inside today's personal computers."
- Lou Gerstner, CEO, IBM, February 2001

The power of networks has helped to reshape modern society. Besides inciting simple efficiencies amongst already performed tasks, these "ideas of the network" are enabling new generations of products and services. In terms of outer space exploration, the envisioned future may include continuous operating outposts and networks on other worlds supporting human and robotic activity. For these missions, enhancing or enabling telecommunication capabilities may be acquired through translating known terrestrial technologies to interplanetary use.

Future concepts of these "space" networks involve the proliferation of more active nodes (spacecraft) throughout the solar system. Many factors have accounted for the upsurge in interplanetary network activity, strikingly seen by the use of ever-greater network resources such as NASA's Deep Space Network (DSN). Some pertinent drivers include transition to smaller and less expensive spacecraft (i.e. multiple Mars Pathfinder/Discovery class missions versus single Voyager-type spacecraft) and more international interest in interplanetary exploration (European Space Agency's Mars Express/Beagle 2, Japanese moon/Mars spacecraft). As these nodes grow the region of interplanetary space will eventually become more interconnected with transitions from lone, disparate missions to coordinated multi-year architectures. At that point terrestrial concepts of networks emerge as case studies to help find optimum architectures (i.e. the Interplanetary Internet). In addition, future exploration (i.e. sample return) and colonization scenarios will require new types of networks.

Utilization of interplanetary resources to enables these types of missions can include the domain of telecommunications. Many times In-Situ Resource Utilization (ISRU) technologies are focused on propulsion, structures, and power. Opportunities may exist to apply the same concept of "living off the land" to orbital and surface telecommunication networks, termed here as In-Situ Communication Utilization (ISCU).

Another motivation for this examination includes the application of known terrestrial capabilities to the realm of interplanetary exploration. Such capabilities are many times never thought of for use in outer space. Space is in many respects a vastly different environment for these technologies. However, a lack of imagination can conceal potentially more efficient paths of exploration.

The philosophy behind this examination originates from a position of non-advocacy with regards to the technology and architecture in question. As much as possible, an independent assessment is performed of this technology. Even though other organizations assisting in the investigation have potential biases towards the technology, a generally philosophy of neutrally is taken. In addition the Principal Investigator (PI) has had no prior funded research relationship on this topic.

PROJECT DESCRIPTION

A feasibility analysis is proposed for a communications architecture based upon reflection of ion trails from meteors in planetary atmospheres. Meteor Burst (MB) communication systems use meteoritic impacts on planetary atmospheres as short burst communication nodes. MB systems consist of semi-continuous, low bandwidth networks. These systems possess both long distance capability (hundred of kilometers) and have lower susceptibility to atmospheric perturbations. Translation of such a system beyond Earth requires an atmosphere; therefore Martian analogues of such a system are presented. Such systems could support planetary mobility (for humans and robots), emergency communications, and weather monitoring stations while minimizing the need for massive orbital telecommunication constellations.

MB telecommunication systems utilize ionized meteor trails for radio signal propagation in the 70-120 km region of Earth's atmosphere to reflect or re-radiate, the RF energy between two stations. The height of the trail allows over the horizon communication. The resultant trails only last from a few milliseconds to several seconds with communication being intermittent and best suited to long range, low data-rate acquisition applications

For this investigation, a feasibility study is proposed of the application of a Meteor Burst (MB) communication system to planetary exploration missions on Mars. Current terrestrial systems should be extrapolated to generate candidate network architectures (a Mars MB communication system with landers and base stations). Meteor Communications Corporation (MCC) and its personnel (developers and patent holders of MB systems, as well developers of the SNOTEL system described above) are associated as technical consultants for this examination.

Current MB systems on Earth consist of master burst stations and remote terminals. The master burst stations typically need several hundred watts of power (200-400 W). Remote terminals have substantially smaller footprints, requiring less than 100 W of power (see Appendix C). These remote terminals do require antennas separate from the telecommunication electronics and sizing issues may be a concern for extrapolation of such systems to the Martian environment.

Sample architectures include global surface nodes with primary missions involving atmospheric circulation observations. For example, in order to facilitate global communication, various high power nodes are scattered throughout the planet. These act as nerve centers that can communicate either directly with Earth or relay information to orbiting satellites. Remote terminals can be placed on various systems: autonomous robots, weather stations, human transport craft, and crewed bases. These central hubs act as conduits of data exchange. Thus remote systems do not have to carry communication equipment to talk with Earth, they can plug into the MB network system. MB systems on Mars are probably best suited for intra-Martian communication: data exchange between assets in or around Mars. Subsequent ground or orbital nodes can be used for relay back to the Earth.

CHAPTER 2: METEORS

OVERVIEW, DEFINITIONS, AND HISTORY

Meteors are ever present in the environment surrounding the Earth. As very small bodies in the solar system (generally smaller than asteroids but larger than atoms or molecules), millions of meteors constantly shower the Earth every day, with the Earth sweeping up approximately 100 million dust-sized meteors every 24 hours.

Observations from interplanetary spacecraft such as Pioneer 10 and 11 (specifically from penetration detectors) show that particle size distribution in the solar system does not change strongly with distance to the Sun[1]. In essence, the spatial density of meteoroids is essentially constant between 1 and 18 astronomical unit (1 AU equals 1.4959787×10^{11} meters). Alternatively, some previous analytical models assume that the spatial density of meteors in the solar system is inversely proportional to heliocentric distance[2]. These particles get caught in the gravity wells of other planets with many of these particles entering atmospheres. Generally these meteors occur due to collisions in the asteroid belt. Others originate from meteor showers produced when a planet crosses a dust stream left along a comet's orbit. This generally results in an increase by a factor of two to three in the metallic concentration in the Earth's atmospheres. Sometimes this increase is an order of magnitude larger during a particularly strong meteor shower. However, the net influx to Earth from these showers is only a small fraction of the total amount due to continuous background impact. Both the time of year and the time of day also influence the total amount of meteor activity in the atmosphere available to visual and radio observation. The tilt of the planet and abundance/rarity of meteor showers contribute to annual fluctuations. An orbiting body's rotation, resulting in meteors being swept up by the gravity field or overtaking the orbiting body, result in the daily variation.

For this examination, a meteor burst will be used to refer to the occurrence of a meteor trail. In order to standard on specific terminology, various definitions related to meteors are given below[3]:

- Meteor: "raised beyond" or "things up in the air"
- Meteoroid: Particle that is "up in the air"
- Meteorite: Particle that survives impact with the surface of a planetary body
- Fireballs: Large, bright meteors (detonating fireball = bolide)
- Classification: Visual, photographic, or radio meteors
- Shower Meteors: From specified orbits, appear to originate from one direction in sky
- Sporadic Meteors: Not associated with showers and random
- Flares or bursts: Sudden and brief enhancements of light during a meteor's passing
- Meteor Path: Geometrical line of motion of the meteoroid
- Meteor Trail: Train of ionization left in or near the path of the meteor

Just as with the other objects in the night sky, humans have been observing meteors for thousands of years. It took the predictable nature of particular storms to begin the scientific process of meteor observation. Historical events that signified scientific exploration of the terrestrial meteor phenomena include:

- 1809 B.C.: In China "stars flew across the sky"
- November 12-13, 1833: Leonid storm over North America
- 1866: Predicted reoccurrence of shower
- 1896: First photographic records

- 1923: First radio wave reflections
- 1932: First meteor spectrography
- 1946: Radar echoes correlated with meteor showers

Terrestrial meteor observation generally disaggregates meteors into types based upon the manner of measurement: visual, photographic, and radio. From some of these observations (and specifically photographic observations) meteoroids can be decomposed into different populations based upon composition, structure, and ablation coefficients[4]. They include:

- Population I: stony material
- Population II: carbonaceous material
- Population IIIA: cometary material
- Population IIIB: soft cometary material

METEOR AND PLANETARY ATMOSPHERES AT MARS

Given the assumptions stated previously about the spatial density of meteors in the near solar system (less than 18 AU), meteoroids could affect the ionosphere structure of other planets as they do on Earth. Mars, Venus, Titan, and Triton are possible other locations in the solar system where meteors would be detectable (visually or in other means) from the surface. This is due in no small part to each of these bodies having a solid surface and thick atmosphere. Given the closeness of Mars to the asteroid belt, such phenomena should be occurring there as well. Dust impact detectors on various interplanetary spacecraft (Cassini, Ulysses) have provided limited data on the size and abundance of some of these particles. For instance the Mars Dust Detector (MDC) on the Japanese Planet-B Nozomi mission to Mars can detect small particles (from 10^{-10} kg to 10^{-18} kg)[1]. Generally, both inner planets (Earth and Mars) share similar characteristics (relative to other bodies in the solar system). Table 1 offers a comparison between selected Earth and Mars properties and Table 2 lists general properties of the Martian atmosphere.

Table 1. General Properties of Mars and Earth

Item	Mars	Earth	Ratio (Mars/Earth)
Mass (10^{24} kg)	0.64185	5.9736	0.107
Volume (10^{10} km^3)	16.318	108.321	0.151
Equatorial radius (km)	3397	6378.1	0.533
Polar radius (km)	3375	6356.8	0.531
Volumetric mean radius (km)	3390	6371	0.532
Core radius (km)	1700	3485	0.488
Ellipticity (Flattening)	0.00648	0.00335	1.93
Mean density (kg/m^3)	3933	5515	0.713
Surface gravity (m/s^2)	3.69	9.78	0.377
Escape velocity (km/s)	5.03	11.19	0.45
GM (x 10^6 km^3/s^2)	0.04283	0.3986	0.107
Bond albedo	0.25	0.306	0.817
Visual geometric albedo	0.15	0.367	0.409
Visual magnitude V(1,0)	-1.52	-3.86	-
Solar irradiance (W/m^2)	589.2	1367.6	0.431
Black-body temperature (K)	210.1	254.3	0.826
Topographic range (km)	30	20	1.5
Moment of inertia (I/MR2)	0.366	0.3308	1.106
J2 (x 10^{-6})	1960.45	1082.63	1.811

Source:
"Mars Fact Sheet", nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

Table 2. General Properties of the Martian Atmosphere

Item	Value
Composition of the atmosphere (by volume)	95.3% carbon dioxide 2.7% nitrogen 1.6% argon 0.13% oxygen Remainder (ppm): Water (H2O) - 210; Nitrogen Oxide (NO) - 100; Neon (Ne) - 2.5; Hydrogen-Deuterium-Oxygen (HDO) - 0.85; Krypton (Kr) - 0.3; Xenon (Xe) - 0.08
Surface Density	~0.020 kg/m3
Scale Height (i.e. The height interval in which the atmospheric pressure changes by a factor of e = 2.7183)	11.1 km
Average air pressure at the surface	6 millibars (1,013 millibars on Earth)
Mean molecular weight	43.34 g/mole
Wind speeds	2-7 m/s (summer), 5-10 m/s (fall), 17-30 m/s (dust storm) (Viking Lander sites)
Average diameter of Mars	6,779 km (about half that of the Earth)
Average distance from the Sun	227,940,000 km (or 1.52 Astronomical Units)
Martian sidereal day (i.e., rotation time)	24 hours, 37 minutes and 22 seconds
Martian solar day (i.e., time between two successive noons)	24 hours, 39 minutes and 35 seconds
Martian year (i.e., time to orbit the Sun):	669.6 Martian solar days or 687 Earth days (1.9 Earth years)
Global average temperature	218 K (-55 °C)
Minimum surface temperature	140 K (-133 °C) (temperature of frozen carbon dioxide on high elevations at the winter pole)
Maximum surface temperature	300 K (27 °C) (dark tropical regions in summer)
Surface area	about the same as the land area on Earth
Highest mountain	Olympus Mons - the largest mountain in the Solar System rising 24 km above the surrounding plain (21.2 km above the reference level**). Its base is more than 500 km in diameter and is rimmed by a cliff 6 km high
Largest canyon	Valles Marineris - a canyon 4,000 km long, up to 5.3 km deep**, and up to 20 km wide.
Largest impact crater and deepest point	Hellas Planitia - an impact crater in the southern hemisphere up to 7.8 km deep** and 2,000 km in diameter
Surface bulge	Tharsis - a huge bulge on the Martian surface that is about 4,000 km across and 10 km high

Sources:
" Basic Facts About The Planet Mars", NASA Ames Research Center Mars Atmosphere Modeling Group, humbabe.arc.nasa.gov/mgcm/faq/marsfacts.html, H.H. Kieffer, B. M. Jakosky, C. W. Snyder and M. S. Matthews (Editors), Mars, University of Arizona Press, Tucson, Arizona, 1992.
"Mars Fact Sheet", nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

Even though the surface atmosphere of Mars is tenuous (1% of Earth), atmospheric densities (and subsequent meteoroid ablation) at altitudes of 120 km are comparable on Earth and Mars. The Martian atmosphere consists of 95% CO_2, 3% N_2, and 2% Ar versus 78% N_2, 21% O_2, and 1% Ar on Earth[2]. This difference is not significant in regards to meteor entry. Observations of meteor spectra indicate that Earth's atmosphere accounts for less than 3% of total luminosity of meteor.

The relation between meteoroid flux at Earth and Mars is related by spatial density and orbital speed of the particles. Specifically, the flux is dependent upon: 1.) The decrease in meteoroid flux due to gravitational focusing by the Earth, 2.) The decrease in spatial number density with increasing heliocentric distance, 3.) The fall-off in speed with heliocentric distance, and 4.) The increase in meteoroid flux due from gravitational focusing by Mars[1].

Previous analyses of meteor stream on Mars have similar atmospheric meteor ablation as on Earth: Specifically these observations include[1]:

- There are approximately five times more asteroids and comets encountering Mars at low velocities (<15 m/s) than the Earth. This is partly due to the mean Keplerian speed drop-off with the heliocentric distance but also due to the weaker gravitational acceleration for meteors hitting the atmosphere of Mars (4.95 km/s for a parabolic meteoroid compared with Earth's 1.1 km/s)
- There appears to be a deficit of intermediate period (Halley-type) Mars approaching comets.

These examinations have indicated methods to detect meteors/meteoroids, but only for scientific use (see Table 3). Such methods have previously included the use of ionization trail radio reflection and detection.

Table 3. Meteor Detection Methods for Scientific Use on Mars[1]

Detection Method	Advantages	Restrictions	Sample Implementation Platform
Surface camera network	Large detection area (Martian atmosphere). Accurate directional information	Requires high data rate transmission capability.	Beagle 2
Density enhancement in Phobos/Deimos ejecta	Potential use as diagnostic of the physical properties of Phobos/Deimos regolith and the dynamical evolution of dust	Small detector area (100 cm^2)	PLANET-B
Ionization trail radio reflection	Sensitive to faint (>+7 m) meteors. Straightforward implementation	Requires at least two stations. Limited direction/velocity information	Beagle 2, NETLANDER
Radar/LIDAR sounding	Provide orbital information	Requires active sounding apparatus	PLANET-B, Mars Express
ELF/VLF wave emission	Omni-directional. Potential use of magnetic field mapping	Applicable only to the largest (>0.1 m) meteoroids	PLANET-B, Beagle 2, NETLANDER
Orbital search with camera or radar	Does not require a landing station. Broad search area.	For camera searched: two-dimensional CCD detector array and multi-second exposure capability necessary	Mars Express

Specifically this includes part of a technical report on planetary atmospheres in which the authors states[1]:

> In the Martian atmosphere the number of natural objects approaching to within 0.2 AU of the planet in question is approximately twice that for Earth. Given for corrections for typical impact speeds the meteoroid flux at Mars is only 50% that of Earth. Subsequently, the height of maximum meteor intensity at Earth and Mars differ. On Earth this intensity

occurs between 70-100 km while on Mars it is between 50-90 km. At these altitudes the atmospheric density is in a range from 10^{-7} to 10^{-9} g/cm^3.

Analytical models for the density of the Martian atmosphere have been developed from measurements by the Mars Global Surveyor (MGS) in April 1996. Specifically temperature, pressure, and atmospheric density are given as follows[5]:

For altitude (h) > 7,000:

Temperature: $T = -23.4 - .00222 * h$ and Pressure: $p = 0.699 * \exp(-.00009 * h)$

For altitude (h) < 7,000 m

Temperature: $T = -31 - .000998 * h$ and Pressure: $p = 0.699 * \exp(-.00009 * h)$

The density is derived from the equation of state: $\rho = p / (0.1921 * [T + 273.1])$ where

T = temperature [degrees Celsius], ρ = density [kg/m^3], p = pressure [KPa], h = altitude [m]

Previous analyses have estimated the rates of meteoric ion deposition in the Martian atmosphere. Figure 1 shows the neutral and ionic deposition rates of magnesium, iron, and silicon in the Martian atmospheric due to an incoming meteoroid flux with an initial velocity of approximately 18 km/s for carbonaceous chondrites[6].

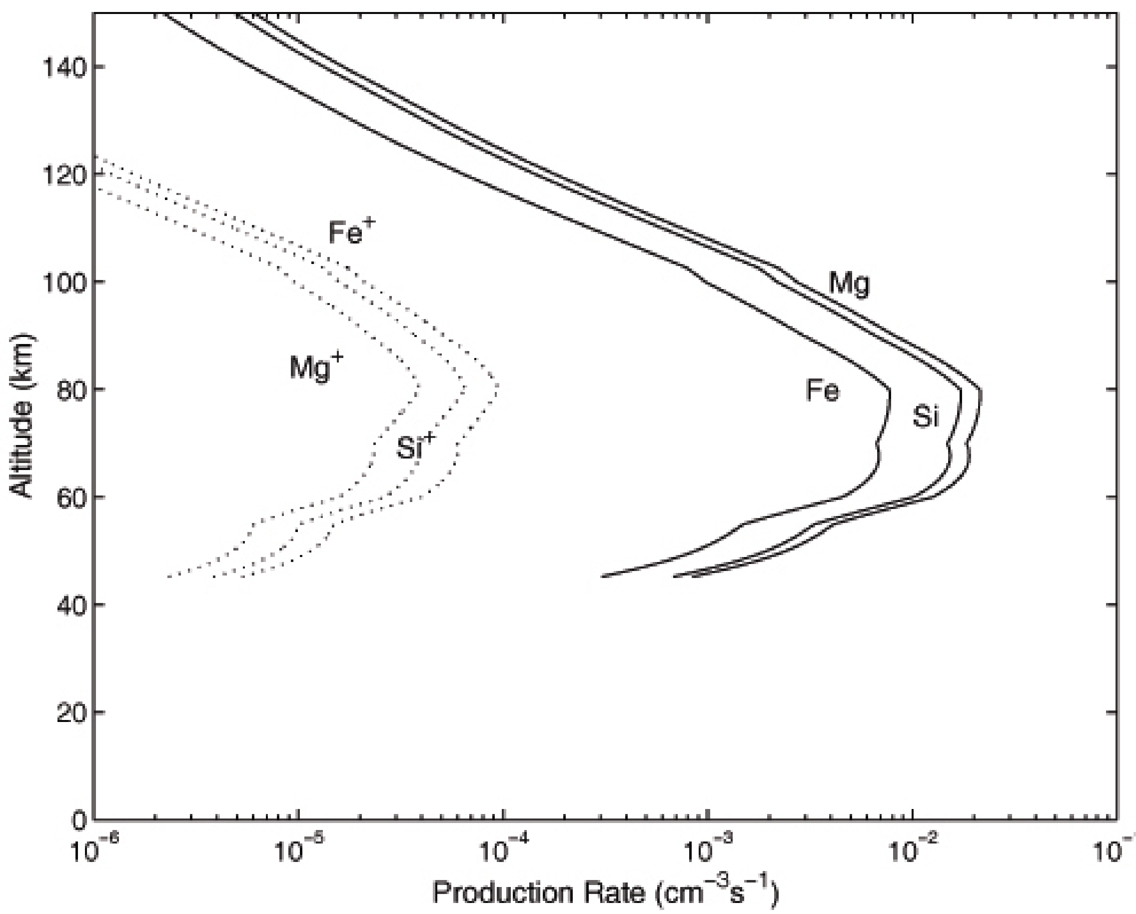

Figure 1. Modeled Neutral and Ion Deposition Rate of Magnesium, Iron, and Silicon in Martian Atmosphere[6]

CHAPTER 3: METEOR BURST (MB) COMMUNICATIONS

OVERVIEW, DEFINITIONS, AND HISTORY

Every day millions of meteors come into Earth's upper atmosphere with enough energy to ionize gas molecules suitably to reflect radio waves and facilitate communications beyond 'line of site'. The ionized trail occurs at altitudes of 100 km with lengths reaching 30 km. The trial sustains itself long enough to support typical network distances of 1800 km. With the capabilities of modern computer processing, MB systems have become both technically feasible and commercially viable for selected applications on Earth.

The initial step to use meteors in this fashion includes detection of a usable ionic trail. A probe signal is sent from one station to another in the network. If there is a meteor trail present, the probe signal is reflected to a receiving station. When another station receives the probe signal, it sends an acknowledgement to the originating station to proceed with data transfer on that trail in a high-speed digital burst. This probe-then-main signal handshaking process occurs each time a burst of data is sent and can occur several times over the course of just one useable meteor trail. Given the need for non-data sending probe signals and error correcting bits; typical transmission data rates vary from a few kilobits per second to over 100 kilobits per second. On Earth, MB links open up hundreds of time per hour depending upon daily and seasonal variations.

During this process of meteor trail ionization, meteors on Earth are entering the upper atmosphere traveling at speeds of 10-75m/s. Large amounts of kinetic energy are converted to heat, vaporizing atoms from the surface of the parent meteor. There is a transformation of kinetic energy into the energy of ionization, striping electrons from the atoms, leaving a trail of positive charged ions and free electrons. The ionization trail is distributed in the form of long, thin parabolic of revolution (typical initial trail radius of 1 m). The electron line density (electrons/meter) is proportional to the mass of the meteor (10^{18} electrons/meter to 10^{10} electrons/meter).

Meteor trails can be subdivided into general classes based upon the magnitude of the electron line density. These two categories include underdense (low electron density) and overdense meteor trails (high electron density). Generally this electron density can be approximated by the mass of the disintegrating meteor (underdense from 10^{-7} g to 10^{-3} g and overdense from 10^{-2} g to 10^{3} g). Characteristics of both types of trails include[7]:

Approximate underdense meteor trail characteristics:

- Free electron density is so low radio waves can penetrate the trail without attenuation
- Each free electron scatters the incoming wave individually, and the total signal received from the trail is the sum of all the signals fro all individual electrons
- Relatively low electron line density ($<10^{14}$ electrons/meter)
- Signals from these trails rise to an initial peak in a few hundred microseconds, then decay exponentially

Approximate overdense meteor trail characteristics:

- When the electron density is high, the central part of the trail behaves like a plasma, radio waves cannot penetrate the core of the trail and are scattered
- Higher electron line density ($>10^{14}$ electrons/meter)
- Reach higher amplitudes than underdense and usually last longer

Table 4 displays the estimated number of sporadic meteors that enter Earth, broken out by those that disintegrate and overdense/underdense types. On Earth, and similar assumptions can be made about Mars, the total mass of all particles at each size is equivalent.

Table 4. Properties of Sporadic Meteors on Earth[7]

Item		Mass [grams]	Radius [cm]	Number swept up by Earth per day	Electron line density [electrons/meter]
Particles that survive passage through atmosphere		10^4	8	10	
Particles that totally disintegrate in the upper atmosphere	Overdense (Visual)	10^3	4	10^2	
		10^2	2	10^3	
		10	0.8	10^4	10^{18}
		1	0.4	10^5	10^{17}
		10^{-1}	0.2	10^6	10^{16}
		10^{-2}	0.08	10^7	10^{15}
	Underdense (Visual)	10^{-3}	0.04	10^8	10^{14}
		10^{-4}	0.02	10^9	10^{13}
		10^{-5}	0.008	10^{10}	10^{12}
		10^{-6}	0.04	10^{11}	10^{11}
		10^{-7}	0.002	10^{12}	10^{10}
Particles that cannot be detected by radio means		10^{-8} to 10^{-13}	0.004 to 0.0002	Total about 10^{20}	Practically None

Meteor bursts were first noticed in detail in the 1930s. In the 1950s, Canada installed a MB system between Toronto and Port Arthur. In the same decade a one-way link was set up between Bozeman, Montana and Stanford, California in the United States. In the 1970s, the Alaska SNOTEL (SNOpacTELemetry) system was installed to provide meteorological information. A specific timeline includes:

- 1930: Pickard noticed that bursts of long distance, high frequency propagation occurred at times of major meteor showers
- 1935: Skellet found that when a meteor entered the Earth's atmosphere, the denser air caused the meteor to heat up and eventually burn, creating an ionized trail which could be used to reflect a radio signal back to Earth, postulated that the mechanism was reflection or scattering from electrons in meteor trail
- 1950s: Canada installs the JANET systems between Toronto and Port Arthur
- 1950s: Bozeman (Montana) and Stanford (California) one way link
- 1970s: Alaska SNOTEL (SNOpacTELemetry) system was installed to provide meteorological information
- 1990s: MCC and SatCom provide commercial MB systems (transport tracking, emergency detection, two-way messaging, vehicle performance monitoring, etc.)

Commercial entities currently offer the service for terrestrial transport tracking, emergency detection, two-way messaging, and vehicle performance monitoring. Current terrestrial examples of MB systems include:

- SNOTEL - 600 Remote Units Measuring Snowpack for 11 Western States
- Philippines Aids to Navigation - Monitoring Lighthouses
- Glacial Lake Outburst Flood (GLOF) Warning Systems
- Pakistan - River and Reservoir Flood Warning
- Egypt - Water Level of the Nile River

- Egypt Aids to Navigation - Port and Lighthouse Monitoring
- Meteor Communications (Europe) - Water Quality Monitoring in the UK

There have been a few previously discovered studies related to using MB systems for telecommunications on Mars. One example includes an abstract from the XXII Lunar and Planetary Science Conference (March 1991, Houston) entitled: "The Potential Use of Meteor Burst Communication Systems on Non-Terrestrial Bodies."[8] Another example stems from a technical report, also at the Lunar and Planetary Institute (LPI), detailing MB use for scientific observation that states[9]:

> As meteors impinge upon and pass through the upper atmosphere and are heated by atmospheric friction, they leave behind trails of ionized plasma which may last for several seconds or longer. Radio waves will be reflected off the ionization trail. A ground-based receiver can be used to detect and count meteor events by the echoes or "pings" of the reflected signal off the ionization trail. Terrestrial meteor-burst communications systems also utilize this concept. On Mars, reflections of the lander-orbiter UHF communications signal can be used to determine the rate of capture of meteors and the height of mass deposition in the atmosphere. These are important parameters because they affect the middle atmosphere chemistry and can provide bounds for numerical models of mass accretion on early Mars.

Generally a review of literature does not indicate any substantial work on the use of MB systems for non-terrestrial telecommunications. There are occasional mentions of these systems for scientific use when Martian meteor observations are discussed in the literature. Even terrestrial MB commercial entities have not explored this application of their technologies. Generally the reduced importance of this technology after the end of the Cold War seems to have resulted in less interest generally for this technology and thus for future applications.

SYSTEM THEORY AND DESIGN CONSIDERATIONS

Characteristic equations relating various properties of the system are developed from expressions detailing peak signal power over the link[10]. Different equations are developed for underdense and overdense trails. Building up from classical MB equations, these equations assist in determining the performance of the system in terms of bits (N_{BMAX}), bit rate (R), and transmission time (t). Depending upon whether a constant bit rate or continuously varying bit rate is used, these equations differ slightly. The examination here does not provide the full derivation and manipulation of these equations but some of the final equations used for modeling purposes.

The initial step is to arrange the geometry of the transmitting and receiving stations. The over-the-horizon geometry of a typical MB system yields a transmitter to trail distance and angle of incidence /reflection as:

$$R_T = R_R = \left[\frac{L^2}{4} + (h + \frac{L^2}{8R_e})^2 \right]^{1/2} \tag{1}$$

$$\sec^2 \phi = 1 + \frac{L^2}{\left(2h + \frac{L^2}{4R_e} \right)^2} \tag{2}$$

To determine the bit rate (for both underdense and overdense trails), bit rate is proportional to received power:

$$R = \frac{P_R}{N_0 (E_b / N_0)_{\mathrm{Re}\, q}} \tag{3}$$

where

the noise factor consisting of external noise, galactic noise, and receiver thermal noise is:

$$N_0 = kT_0 \left[\frac{104}{L_R} \left(\frac{\lambda}{15} \right)^{2.3} + F \right] \tag{4}$$

For the underdense case, received carrier power, time-independent component of received carrier power, transmission time, bit rate, and number of bits (for constant and continuously varying bit rates) are:

$$P_R(t) = P_R(0) \exp\left[\frac{-2t}{t_c} \right] \tag{5}$$

$$P_R(0) = \frac{P_T G_T G_R \lambda^3 q^2 r_e^2 \sin^2 \alpha}{16\pi^2 R_T R_R (R_T + R_R)(1 - \cos^2 \beta \sin^2 \phi)} \cdot \exp\left[\frac{-8\pi^2 r_0^2}{\lambda^2 \sec^2 \phi} \right] \tag{6}$$

$$t_c = \frac{\lambda^2 \sec^2 \phi}{16\pi^2 D} \tag{7}$$

$$t_{opt} = \frac{t_c}{2} = \frac{\lambda^2 \sec^2 \phi}{32\pi^2 D} \tag{8}$$

$$R_{opt} = \frac{P_R(0)}{e N_0 (E_b / N_0)_{\mathrm{Re}\, q}} \tag{9}$$

$$N_{BMAX1} = t_{opt} R_{opt} \tag{10}$$

$$N_{BMAX2} = e t_{opt} R_{opt} \tag{11}$$

For the overdense case, received carrier power, time-independent component of received carrier power, transmission time, bit rate, and number of bits (for constant and continuously varying bit rates) are:

$$P_R(t) = P_R(0) \left[\frac{r_0^2 + 4Dt}{\sec^2 \phi} \ln \frac{r_e q \lambda^2 \sec^2 \phi}{\pi^2 (r_0^2 + 4Dt)} \right]^{1/2} \tag{12}$$

$$P_R(0) = \frac{P_T G_T G_R \lambda^2 \sin^2 \alpha}{32\pi^2 R_T R_R (R_T + R_R)(1-\cos^2 \beta \sin^2 \phi)} \qquad (13)$$

$$t_{opt} = \frac{r_e q \lambda^2 \sec^2 \phi}{8\pi^2 D} \qquad (14)$$

$$R_{opt} = \frac{P_T G_T G_R}{128\pi^3 N_0 (E_b / N_0)_{\mathrm{Re}q}} \left[\frac{\lambda}{R_T}\right]^3 \left[\frac{r_e q}{e}\right]^{1/2} \qquad (15)$$

$$N_{BMAX1} = t_{opt} R_{opt} \qquad (16)$$

$$N_{BMAX2} = 2 t_{opt} R_{opt} \qquad (17)$$

where

the symbols are described in Table 5.

Table 5. Symbolic Notation for Characteristic Equations

Symbol	Sample Value	Units	Description
h	75,000	m	trail altitude
L	500,000	m	great circle distance between terminals
R_T	263,798	m	distance from the transmitter to the trail
R_R	263,798	m	distance from the receiver to the trail
R_e	6,400,000	m	radius of the planet (Earth default, 3,397,000 m for Mars)
P_T	200	W	transmitter power
G_T	0.18	dB	transmitting antenna gain
G_R	0.04	dB	receiving antenna gain
λ	6	m	Wavelength
q	1.00E+14	electrons/m	electron line density of the trail
r_e	2.82E-15	m	classical radius of the electron
α	90	degrees	angle between the electric field vector E at the trail and RR
r_o	0.65	m	initial radius of the trail
D	2.04929	m^2/s	diffusion coefficient, default=10
ϕ	0	degrees	half the angle between RT and RR (i.e. the angle of incidence/reflection)
β	90	degrees	angle between the principal axis to the trail and the plane formed by RT and RR
$(E_b/N_o)_{required}$	7.94	9.00	ratio of received energy per bit to noise power spectral density required by modem for specified bit error rate and type of modulation
k	1.3805E-23	J/K	Boltzmann's constant
T_o	290	K	Temperature
L_R	1.3		power loss ratio between the antenna and receiver
F	2.5		receiver noise contribution, receiver thermal noise
t_{opt}	0.54	seconds	optimum transmission time
R_{opt}	0.004	kbps	optimum bit rate
N_{Bmax}	0.002	kbits	maximum number of bits that can be obtained from a single trail (1 for constant bit rate, 2 for continuously varying bit rate)

For this examination the ambipolar diffusion coefficient was adjusted to reflect the different densities of the Martian atmospheric relative to the Earth. This diffusion coefficient gives the speed of diffusion of the ions and electronics in the trail:

$$D = \frac{7\mu_a}{8\rho_a\sigma}\sqrt{\frac{kT}{\pi\mu_m}} \tag{18}$$

where

μ_a = mean mass of atmospheric atoms
ρ_a = atmospheric density
σ = collision cross section of meteoric atoms with atmospheric atoms (~$7x10^{-19}m^2$)
μ_m = mean mass of meteoric atoms
T = temperature

The diffusion coefficient is highly correlated with atmospheric density. Generally better values for this parameter emerge with better atmospheric models. On Earth an approximation for the above equation can be utilized:

$$\log_{10} D = 0.067h - 5.6 \tag{19}$$

where

h = altitude [km]

A correction factor to determine the diffusion coefficient was utilized based upon the estimated density of both the Martian and Earth atmosphere at two data points (50 and 100 km). The correction factor consisted of:

$$\frac{\rho_{earth}}{\rho_{Mars}} = -0.2045h + 26.077 \tag{20}$$

The antenna gain for this design is characterized as the ratio of the effective aperture area to the effective area of a hypothetical isotropic antenna. The boresight gain is given in terms of the size of the antenna:

$$G = \frac{\pi^2 D_r^2 \eta}{\lambda^2} \tag{21}$$

where

G = Gain [dB]
D_R = antenna diameter [m]
η = net antenna efficiency which depends on the electric field distribution over the antenna aperture and the total radiation efficiency (η^* = Power/$Power_{in}$) associated with various losses including spillover, ohmic heating, phase nonuniformity, blockage, surface roughness, and cross polarization

All of the above relationships can be utilized together to create a system level model linking various input parameters such as power, antenna diameter, station distance, and meteor trail height to output bit rate and transmission time, adjusted for the environment of Mars. The above relationships also yield particular insight into some of the design considerations for meteor communication systems. General guidelines useful in the design of MB systems include[7]:

- Power received is proportional to the cube of the wavelength thus limiting thus generally limiting the maximum useful frequency to below 80 MHz (for generally lower power systems), on Earth frequencies in the 40-70 MHz range are used
- Given many factors, including the more unpredictable natures of overdense trails, underdense trails will be utilized more often
- Number of detectable meteors is proportional to the square foot of the transmitter power and antenna gains
- Number of detectable meteors is also proportional to 3/2 power of the wavelength
- Narrower beam, higher gain antennas are not more of an advantage, since the portion of the sky illuminated normally is reduced, reducing the number of usable meteor trials, this negates the increased sensitivity possible with higher gain antennas
- Communication times are generally kept to a minimum, burst duration on Earth for a 1,000 km range is 0.25 seconds at 50 MHz
- Lower data rates used when message waiting time more important than total data transmitted for a specific period of time
- Hot spots depend upon time of year, time of day, random distribution of sporadic meteors
- Nominally data rates for MB systems range from several kilo-bits-per second (kbps) to under 100 kbps, higher rates are possible with full-duplex communications mode where higher gain antennas and higher power transmitters are used at both ends of the link
- Increasing the data rate decreases the received power/bit for a total fixed transmit power, this decreases the maximum allowable path loss, that in turns decreases the number of usable meteor trails (doubling the bit rate decreases the maximum allowable path loss by 3 dB and reduced the number of usable trails by about 40%)
- Data rate increases are limited by the effect of increasing system sensitivity resulting in more use of overdense trails and also by increase in the waiting time between communication passes, lower data rates are used when message waiting time is more important than the total data transmitted during a specific period of time
- Meteor spots exist that require antenna beam widths to be in the 40 to 50 degree range limiting the maximum usable antenna gains to approximately 12 to 14 dBi
- Objectives of system design include adjustment of the base-to-remote link (by adjusting base transmit power or receiver threshold) to balance the remote-to-base link
- A natural Time-Division-Multiplex (TDM) feature is inherent within all meteor burst networks allowing thousands of stations to operate within a network on a single frequency
- When two stations are within 50-150 km of each other, the ground wave phenomenon inherent to VHF radio occurs (known as extended line-of-sight)

CHAPTER 4: MARTIAN METEOR BURST (MB) COMMUNICATIONS

CONCEPT OVERVIEW

Future robotic exploration of Mars I driven by the use of smaller, less expensive spacecraft with more focused instrumentation for each specific mission. Thus over the decades the number of science instruments per mission has diminished as the grand exploration spacecraft (Voyager, Galileo) have been replaced with more focused platforms (Pathfinder, Mars Odyssey). However, telecommunications is an ever-present challenge within all these missions. The particular terrestrial technology of Meteor Burst (MB) communications is applied to the domain of interplanetary exploration. These telecommunication architectures are based upon reflection of trails from meteors in planetary atmospheres. Specifically a case study involving application of the technology to Mars is examined. Such Meteor Burst (MB) communication systems consist of semi-continuous, low bandwidth networks possessing both long distance capability (hundred of kilometers) and lower susceptibility to atmospheric perturbations. For this initial study, it is assumed that MB systems on Mars are probably best suited for intra-Martian communication: data exchange between assets in or around Mars with subsequent ground or orbital nodes used for data relay back to the Earth.

As on Earth, master and remote stations make up the bulk of the surface telecommunications infrastructure. An envisioned architecture for use on Mars could include the use of regional sets of MB networks (consisting of one master station and several remote stations). Disparate regional networks could be linked together and scattered throughout the planet. Generally, in order to facilitate global communication and science gathering, various higher power master nodes could be scattered throughout the planet, acting as nerve centers that relay information to other master stations or orbital satellites. Remote terminals could be placed on various systems: autonomous robots, weather/circulation monitoring stations, human transport craft, and crewed bases (potentially acting as central conduits of data exchange). Figures 2 and 3 show conceptual storyboards of potential MB systems on various machines in Mars. These include rovers, insect robots, gliders, etc. Figures 4 and 5 show conceptual implementations of MB systems on lander stations. Figures 6, 7, 8, and 9 illustrate the potential of these systems on robots and perhaps to even assist future human surface exploration. These conceptual illustrations and renders are meant to portray the imagined possibilities of MB systems and are based on specific technical design.

ARCHITECTURE ANALYSIS

For this examination, the initial mission for a sample Mars MB telecommunications system was based upon the rationale of regional and global networks monitoring a limited number of atmospheric parameters. One motivation for Martian exploration is to understand the general circulation of the atmosphere on a near global scale. Such global network science for meteorology may only require surface assets equipped with limited instrumentation, specifically monitoring surface pressure over time. Previous studies have given estimates for the number of stations to adequately study such atmospheric phenomena (see Table 6). Given such science requirements, latitudinal deployment of such mini-meteorological (or Mini-Met) stations would be needed with separation by no more than 20 degrees of latitude if using between ten to twenty surface stations[11].

Previous studies have examined the use of UHF radio links with orbital satellites to reduce the onboard telecommunication mass, transmission power, and antenna pointing recruitments for surface stations. Some architectures use the concept of a Mars Relay Satellite (MRS) to coordinate data from multiple surface stations[12]. These surface nodes consist of many types of elements enabling different science missions, lifetimes, and data rates (see Table 7). Generally, there is a substantial reduction of surface requirements if some of the Earth-relay telecommunications is off-loaded to orbital nodes (see Table 8). Similarly for a MB system, part of the telecommunication load is off-loaded, not to orbital nodes, but through the use of MB links.

Table 6. Estimate of Number of Mars Surface Stations to Study Various Atmospheric Phenomena[11]

Atmospheric Feature-Related Issues	Minimum Number of Surface Stations, N	Location
Zonal-mean circulation-momentum, wave processes, energy transfer	15	Spread in longitude, over +/- 70 degrees latitude
Mid-latitude waves (e.g. baroclinic and stationary)-energy transfer, dust raising	12	7 equi-space in the northern hemisphere around 60 degree N, 5 in the southern hemisphere around 50-60 degrees S
Equatorial waves-tracer transport, dust raising	3	15 degrees S, equator, 15 degrees N, at widely space longitudes
Thermal forcing	-	All of the above
Mesoscale system-regional winds, frontal structures, slope winds	3	At the vertices of a triangle, with ~300 km side length, to obtain the geostrophic wind vector
CO_2 cycle and mean global pressure-interactions with the general circulation, polar hear balance	16	Spread in latitude and longitude, approximately evenly. The large number is required to define the global mean pressure
Dust storms-control of climate and aeolian features	8	2 at the equator, 2 at 35 degrees S, 2 at 20 degrees S, 2 at 15 degrees N, at storm longitudes

Table 7. Potential Mars Mission Elements[12]

Mission Element	Science Instrument Types	Lifetime at Mars [years]	Frequency of Contact (per lander) [per sol]	Data Return Volume (per lander) [Mb/sol]	Command Volume (per Lander) [b/sol]
Full Science Lander	seismology, geoscience, meteorology	2-6	~1	10	1,000
Geoscience Lander and/or Rover	geoscience, meteorology	0.1-1	~1	1	1,000
Mini-Met Lander	meteorology	2-6	~0.1	1	<100
Balloon	meteorology, imaging, spectrometry	0.1-1	~1	1	200
Pentrator	meteorology, geochemistry	0.1-2	~1	1	200

Note: geoscience includes: imaging, spectrometry, and chemical analysis, 1 sol = 1 Martian day (24.6 hours), Mini-Met Lander has limited power

Table 8. Comparison Between Relay and Direct Earth Communication Performance For a Mars Surface Station[12]

Parameter	Using Mars Relay Satellite (MRS)	Direct Surface Relay To Earth
RF Transmit Power	<0.5 W (UHF)	~5.5 W (X band)
Transmitter Input power	~ 1 W	~ 15 W
Antenna	Hemispherical coverage	0.2 m dish
Antenna pointing	None	
Data Return Volume	10 Mb/sol	2.88 Mb/sol (8 hour pass)

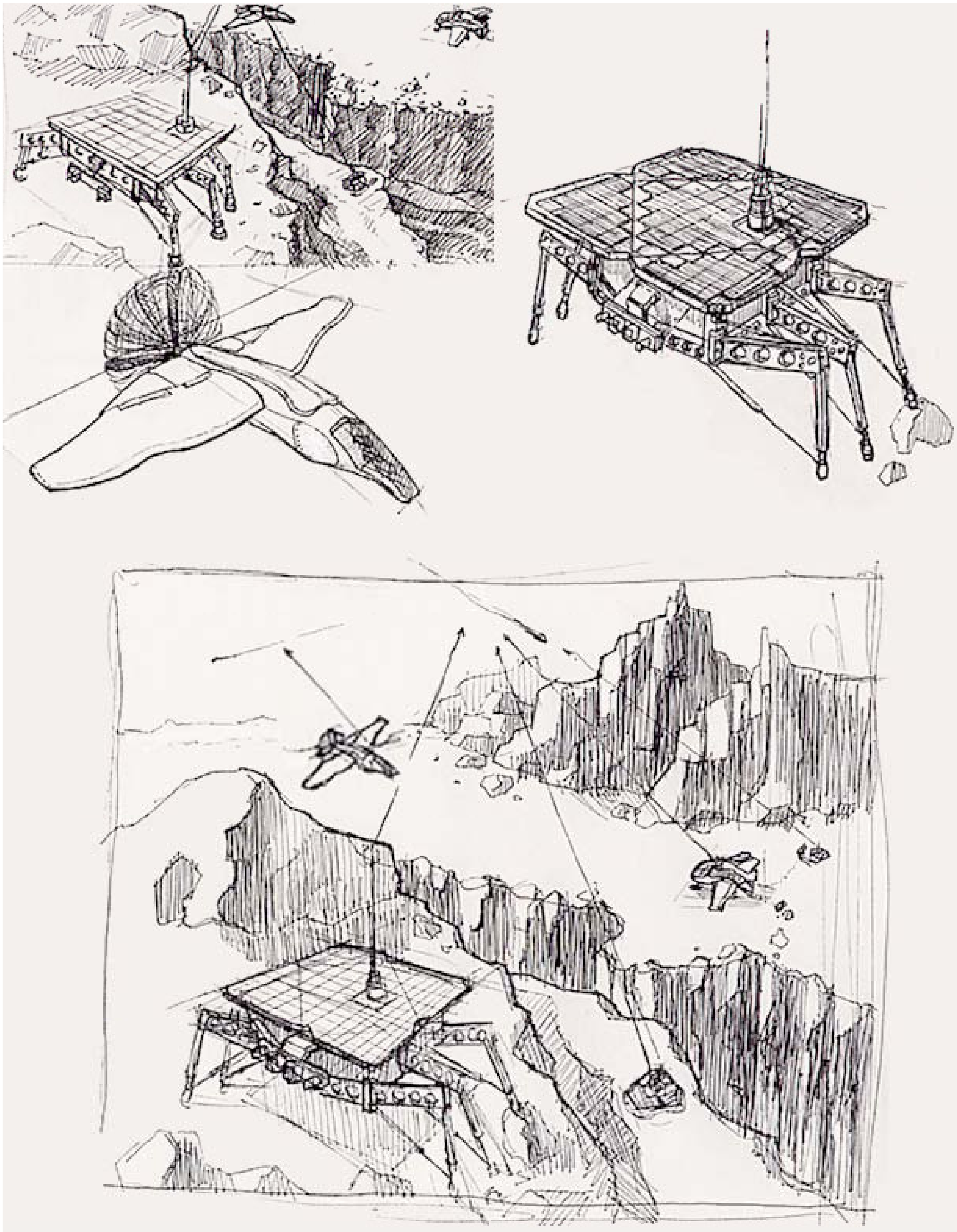

Figure 2. Conceptual Storyboards of Meteor Burst (MB) Telecommunication Robotic Platforms on Mars

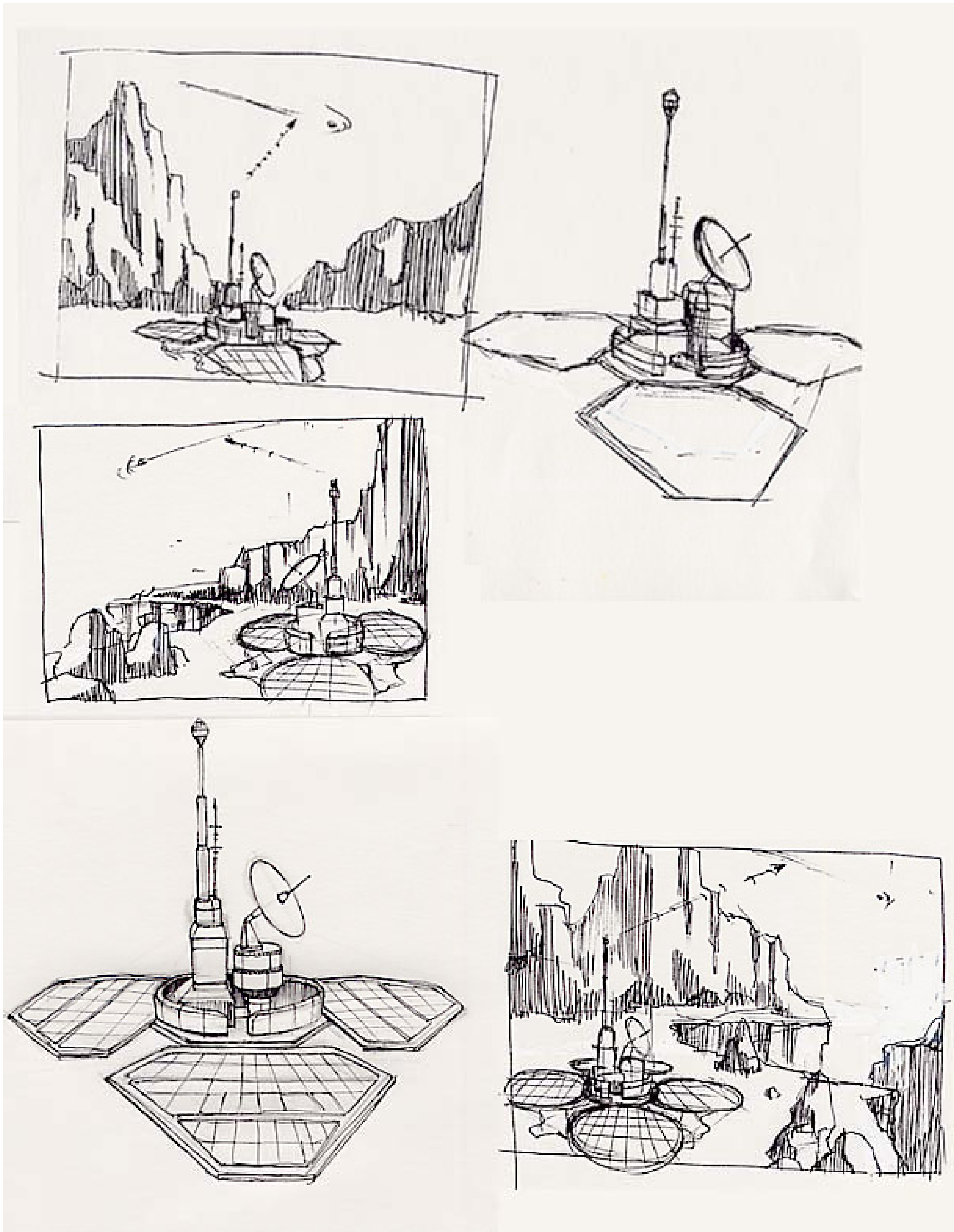

Figure 3. Conceptual Storyboards of Meteor Burst (MB) Telecommunication Lander Platforms on Mars

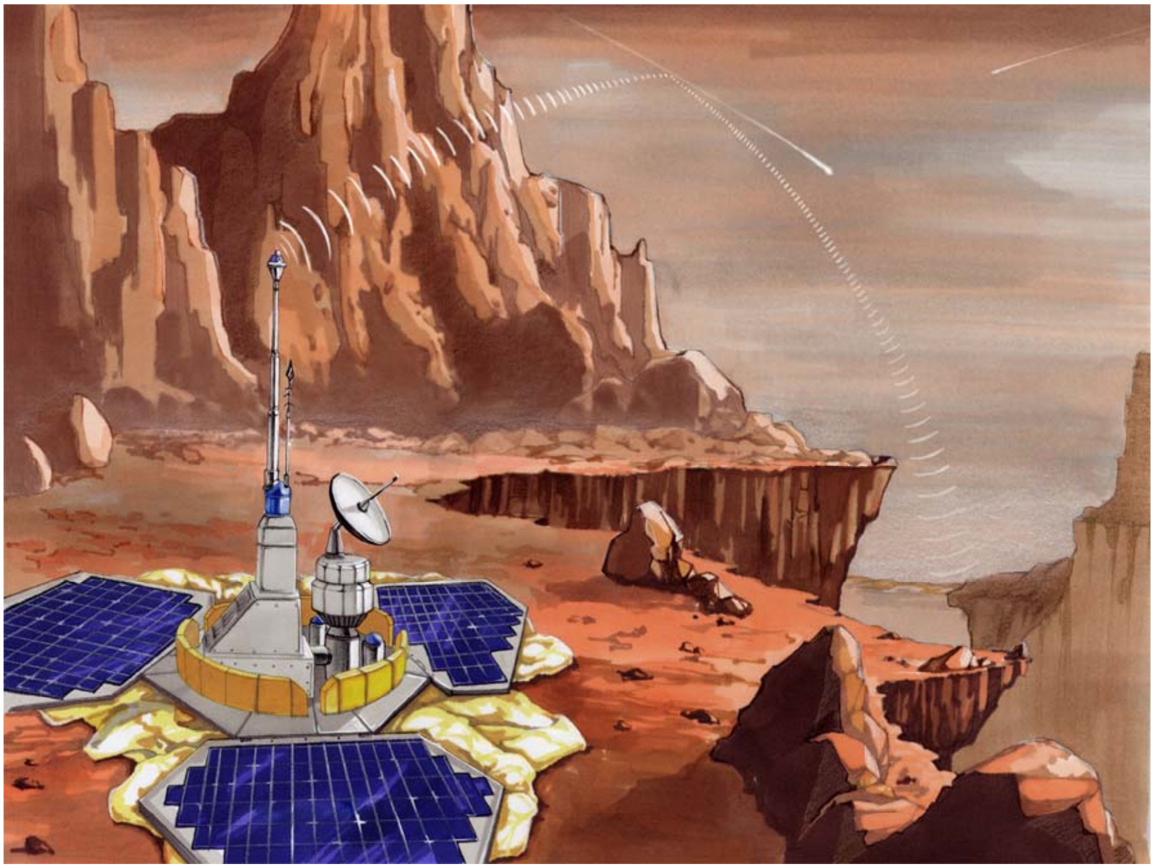

Figure 4. Conceptual Illustration of Meteor Burst (MB) Telecommunication Lander Platform on Mars

Figure 5. Conceptual Render of Various Meteor Burst (MB) Telecommunication Platforms on Mars

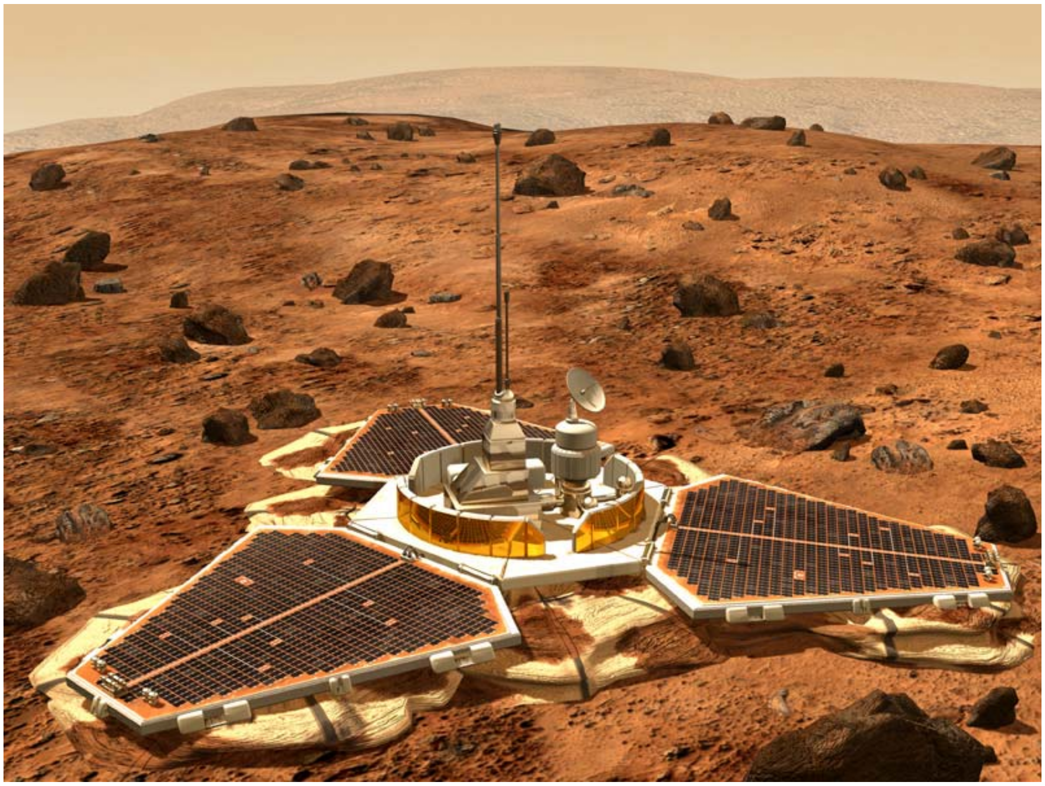

Figure 6. Conceptual Render of Meteor Burst (MB) Telecommunication Lander Platform on Mars

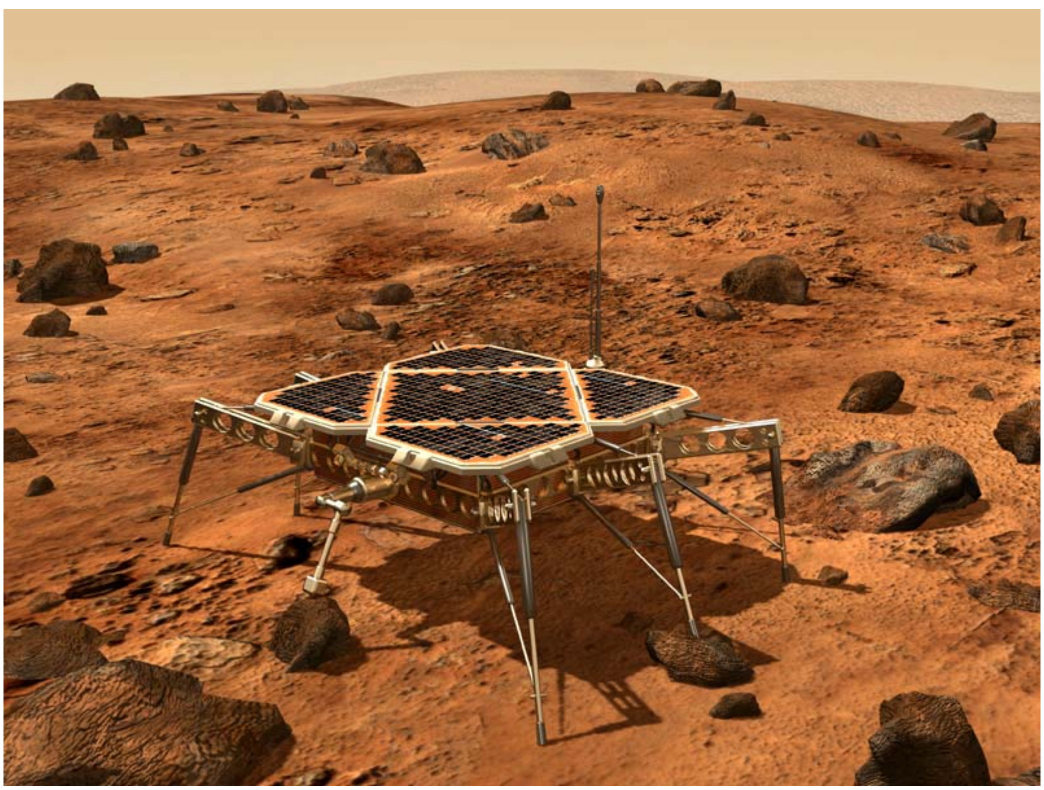

Figure 7. Conceptual Render of Meteor Burst (MB) Telecommunication Insect Robot Platform on Mars

Figure 8. Conceptual Render of Meteor Burst (MB) Telecommunication Human Platform on Mars (side)

Figure 9. Conceptual Render of Meteor Burst (MB) Telecommunication Human Platform on Mars (back)

CHAPTER 5: SYSTEM MODELING AND SIMULATION

MODELING

Modeling helps to determine the properties of a technically feasible design. In the conceptual design stage, modeling can include the use of monolithic synthesis/sizing codes or integrated disciplines in a multi-disciplinary environment. These models are representations of the real world based on processes in terms of physics, human operations, economics, etc.

The metrics used to evaluate a conceptual system can be composed from various disciplines (i.e. performance, operations, cost, economics, safety and reliability) representing both a system's technical feasibility and economic viability. Uncertainty, an ever-present character in the design process, can also be embraced through a probabilistic design environment[13]. The objective is to probabilistically quantify the impact of parameters on the output metrics of interest from the full design process, notionally referred to here as Probabilistic Data Assessment (PDA)[14]. Robust design methods such as PDA allow quantitative assessment of risk. Monte Carlo simulation techniques can be used to place uncertainty distributions on internal design parameters. The resultant outputs are cumulative and frequency probability distributions rather than simple deterministic values. Confidence intervals can be placed upon output metrics of interest to determine the 80% or 95% likelihood of meeting a target (e.g. payload capability, dry mass, life cycle cost). In order to use probabilistic (or Monte Carlo) methods in a time judicious manner, both recalculation time and memory requirements need to be addressed.

The above conceptual design process is presented here in a collaborative design environment. Based upon Phoenix Integration's ModelCenter© and Analysis Server© environment, this allows separate platform engineering codes of various fidelities to interact through the Internet and become coupled to each other. Within this environment optimization, trade studies, Design Of Experiments (DOE), Response Surface Methodology (RSM), and Monte Carlo techniques can be employed very efficiently across multiple computing platforms.

This examination utilizes many engineering level algorithms to design a Martian Meteor Burst (MB) master/remote station link architecture. This examination does not use all the possible engineering disciplines available for such a design process. Only the most relevant disciplines that impact the final output metrics (such as data transmission rate and system mass) in a substantial manner are detailed here. Specific disciplines in the current modeling process include: antenna sizing, link geometry, link power, link performance, and master/remote station mass models. The design process described herein uses probabilistic methods to generate the system level output metrics of interest for a Martian MB conceptual design in a collaborative design environment. Both system sensitivity and uncertainty assessment is performed to determine the critical performance parameters of the system.

ROSETTA Analysis Process

In order to negate the computational expense involved with the use of Monte Carlo uncertainty simulation (potentially thousands of converged designs), a time-efficient process is needed for concept simulation and technology evaluation. Meta-models, or representations of these detailed models, can be employed for situations where computation and monetary expense are to be minimized. Therefore, the Reduced Order Simulation for Evaluation of Technologies and Transportation Architectures (ROSETTA) modeling process is employed[15].

A ROSETTA model is a spreadsheet-based meta-model which is a representation of the design process for a specific architecture (e.g., ETO, in-space LEO-GEO, HEDS, landers. orbiters). In a ROSETTA model, each traditional design discipline is represented as a contributing analysis in the Design Structure Matrix (DSM). ROSETTA models contain representations of the full technology evaluation step. Individual developers of each ROSETTA model determine the depth and breadth of the appropriate contributing analyses (see Figure 10). ROSETTA models are grouped into three categories, which signify their level of development:

- Category I: Produces traditional physics-based outputs such as system weight, size, payload, and/or the NASA metric in-space trip time
- Category II: In addition to items in Category I, adds operations, cost, and economic analysis outputs such as turnaround time, life cycle cost, cost per flight, internal rate of return (IRR), and the NASA metric price per pound of payload
- Category III: In addition to items in Category II, adds parametric safety outputs such as catastrophic failure reliability, mission success reliability, and the NASA metric probability of loss of passengers and/or crew

The ROSETTA modeling process was developed at the Georgia Institute of Technology and enhanced at SpaceWorks Engineering, Inc. (SEI). It has been adopted by the Integrated Technology Assessment Center (ITAC), sponsored by NASA's Marshall Space Flight Center's Advanced Space Transportation Program (ASTP), for research on future space transportation systems. For this study, the ROSETTA Category I modeling process was applied to the Martian MB telecommunications system. The fundamental principals of the ROSETTA meta-model design process still apply. These types of models can subsequently be used for technology prioritization processes such as the Abbreviated Technology Identification, Evaluation, and Selection (ATIES) methodology employed by SEI[16,17].

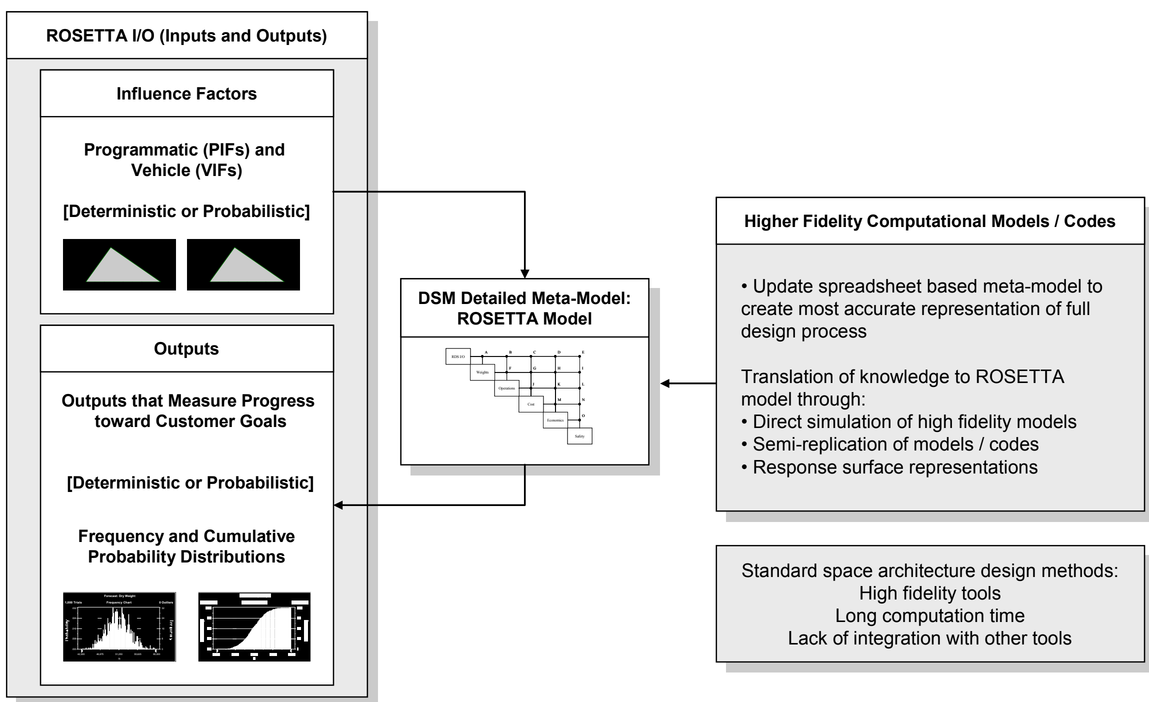

Figure 10. Integration of Main-Line Tools within a Robust ROSETTA Model

The ROSETTA model for this Martian Meteor Burst (MB) telecommunication system involved representing the link geometry and subsequent master and remote station spacecraft sizing. The model is able to determine the data rate and transmission time for a burst of data given certain parameters in regards to the power levels, antenna sizes, and the relative positions of the master and remote stations with respect to each other. The current incarnation of the ROSETTA model can represent one master station and one remote station. The master station can transmit at a higher power than the smaller remote station. This information is passed along to subsequent master and remote station spacecraft sizing and mass relationship algorithms to determine spacecraft mass. The Design Structure Matrix (DSM) in Figure 11 relates the relationships between the various Contributing Analyses (CAs) in the model. The station mass and sizing CAs (for both the master and remote stations) are themselves made up of more complex models (see Figure 12 for a detailed DSM of the master and remote station spacecraft sizing and mass estimation).

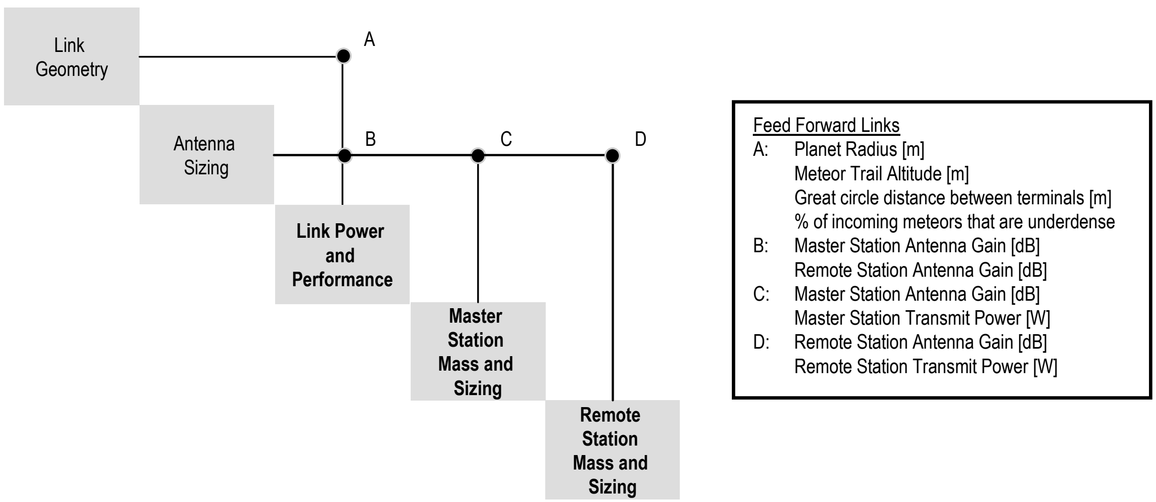

Figure 11. Meteor Burst ROSETTA Model: Design Structure Matrix (DSM)

Sample technology and architecture assumptions for the current incarnation of the MB ROSETTA model include:

- Spacecraft (master and remote station) sizing and mass estimation is performed only for post Mars Entry, Descent, and Landing (EDL) phases, a trajectory allowance is provided for the EDL phase and subsequent landing thruster and propellant mass estimation is performed
- Solar collection is the only power generation source assumed for this current examination, the solar cell area is sized for a one year surface life for both the master and remote stations; with photovoltaic (PV) specific mass of 10 kW/kg, assuming a 35% solar cell degradation factor over this time
- Powered Entry, Descent, and Landing (EDL) are assumed for both the master and remote station landers using heat shields, parachutes, and chemical thrusters; hydrazine is the baseline landing propellant chosen for both type of spacecraft
- Minimal science payload is assumed for both the master and remote stations (five kilograms for the master station and two kilograms for the remote station, each payload requiring approximately five watts of power during maximum power consumption period)
- The specific mass of the MB telecommunication sub-system varies from 56.8 kg/kW of transmitted power for the master station to 17.2 kg/kW of transmitted power for the remote station (these values are based upon specific masses of current terrestrial MB systems)

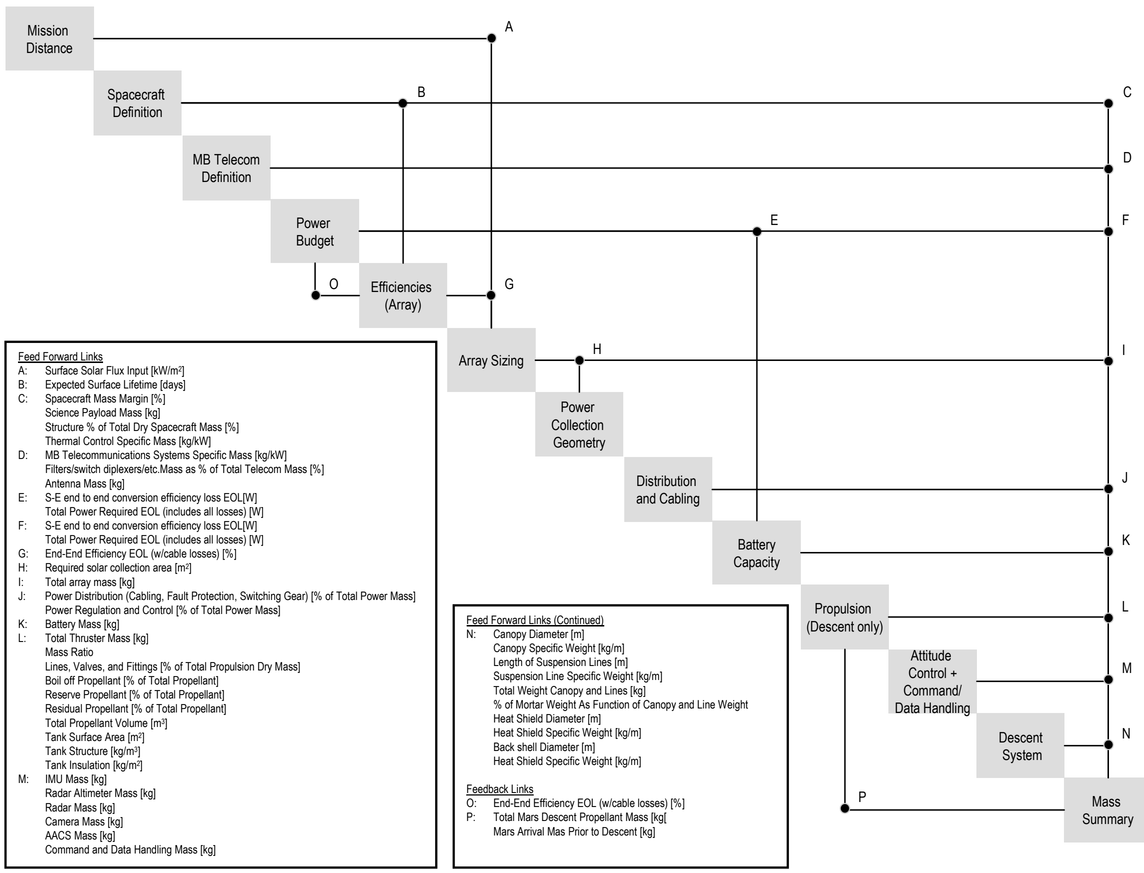

Figure 12. Meteor Burst ROSETTA Model: Surface Station Mass and Sizing Design Structure Matrix (DSM)

Collaborative Design Environment (CDE)

The disciplinary engineering model is used in a collaborative engineering framework based upon Phoenix Integration's ModelCenter© and Analysis Server© platforms. These tools allow the designer to join disparate models and simulations together in a unified environment wherein each discipline can interact with any other discipline. This is performed through a visual interface of an engineering workflow of events where inputs and outputs from various models can be linked together (called a ModelCenter© "model"). This interface allows the engineering process to be more automated and flexible with regards to computing platforms since ModelCenter© and Analysis Server© are relatively platform independent. In addition, these products allow disciplinary models (or ModelCenter© "components") to be located at diverse geographical locations since data exchange can be performed seamlessly in the environment through the Internet. Driver components besides the models and simulation themselves can be added to the environment. These can include optimizers, trade studies, Design of Experiments (DOE), as well as Monte Carlo components.

A suite of uncertainty and sensitivity analysis tools that can be coupled with the ModelCenter© collaborative design environment was used for this examination. Developed by SpaceWorks Engineering, Inc. (SEI) and entitled ProbWorks, this suite initially consists of four tools to help employ uncertainty analysis techniques, each implemented as a Java-based component which can function on any platform running ModelCenter© and Analysis Server©. The direct Monte Carlo driver and the faster DPOMD approximation driver propagate the influences of uncertainty in input parameters through a user's disciplinary tool to assess the likely outcomes in terms of statistical parameters such as mean, standard deviation, certainty level, and skewness. Supporting tools for the generation of fast-acting polynomial response surface equations (RSEs) and Pareto sensitivity analysis for variable screening are also included in the package.

SIMULATION RESULTS

Model Sensitivity

Different sensitivities analyses were performed on the MB ROSETTA model in order to better grasp the implications of various input parameters upon output metrics of interest. These results provide insight into the performance of a MB system in the Martian domain with corrections for the atmosphere and meteor trail height versus on Earth. All of the subsequent analyses (including the later probabilistic results) assume the presence of only underdense trails and constant (versus continuously varying) bit rates. These are taken as more conservative assumptions in order to obtain the first set of output data while retaining the flexibility to model varying percentages of underdense and overdense trails. The sensitivities shown below consist of either one-variable or two parameter value sweeps against one dependent variable. The independent variables assumed for the model (and their baseline values) include:

- Distance between surface nodes (between master and remote station) [500 km]
- Altitude of meteor burst trail [75 km]
- Wavelength [6 m]
- Transmission power [200 W]
- Transmit antenna diameter [1.0 m]
- Receive antenna diameter [0.5 m]

Figures 13 through 15 show a one variable sweep against the surface node distance (from a master station to a remote station) for transmission time [seconds], bit rate [kbps], and number of bits [kbits]. Figure 16 shows the linear relationship between the MB telecommunication specific mass and overall spacecraft Mars arrival mass. Figures 17 through 21 show the two variable sweeps for the same output metrics but this time using some of the additional independent model variables listed above.

These initial deterministic findings from the ROSETTA model indicate that the Martian MB system, given constraints such as antenna size and power, yield worse data rates than similar systems on Earth. As the distance between nodes increases, the transmission time increases (until somewhere past 1,500 km where a decrease occurs) with the data rate decreasing over distance. Generally, with node spacing distances greater than 1,000-1,500 km, the bit rate drops to non-usable levels with the number of bits below 0.0005 bits. Trail altitudes over 70 km do not affect transmission time or bit rate unless the distance between nodes is very close (less than 500 km). Higher wavelengths non-linearly increase transmission time, but at smaller wavelengths transmission power becomes a more dominate factor in affecting bit rate. The bit rate is more sensitive to receive antenna diameter than transmit antenna diameter (increasing the receive antenna diameter from 0.25 m to 1 m increases bit rate from less than 0.01 kbps to greater than 0.06 kbps). The preliminary findings indicate that the receive antenna should be as large as possible for these systems and that the trail altitude on Mars (lower than that on Earth at 50-90 km) still generates some usable bit rate (0.01 to 0.03 kbps) with transmission times under one second. Given these various factors, a MB system with closer spacing between master and remote stations than that on Earth could have some usable data rate potential.

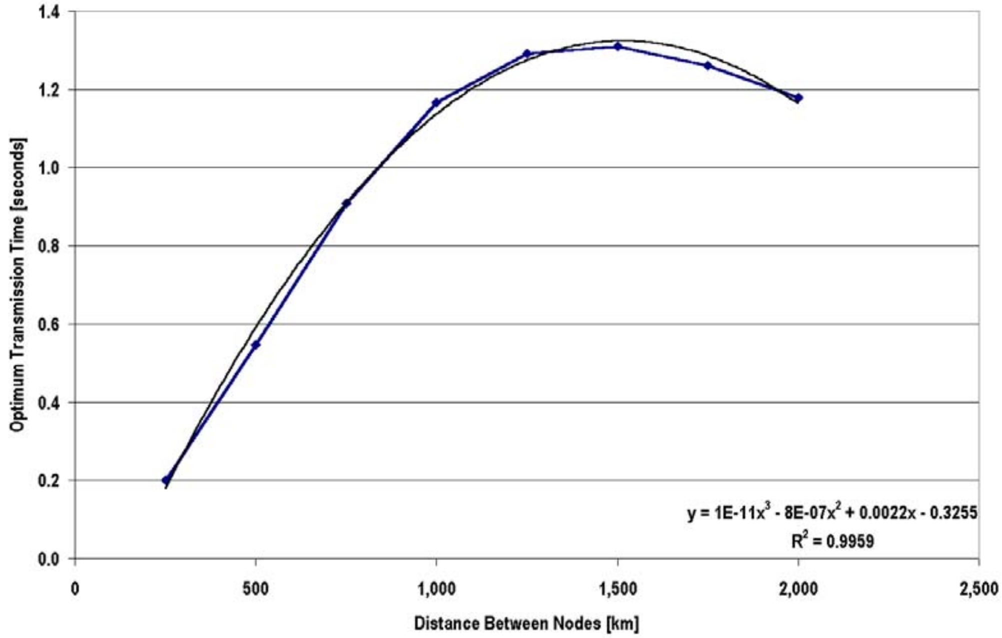

Figure 13. Underdense Trail Transmission Time Sensitivity
(constant bit rate, underdense trail, input antenna power = 200 W, transmit antenna diameter = 1.0 m, receive antenna diameter = 0.5 m, wavelength = 6 m, trail altitude = 75 km)

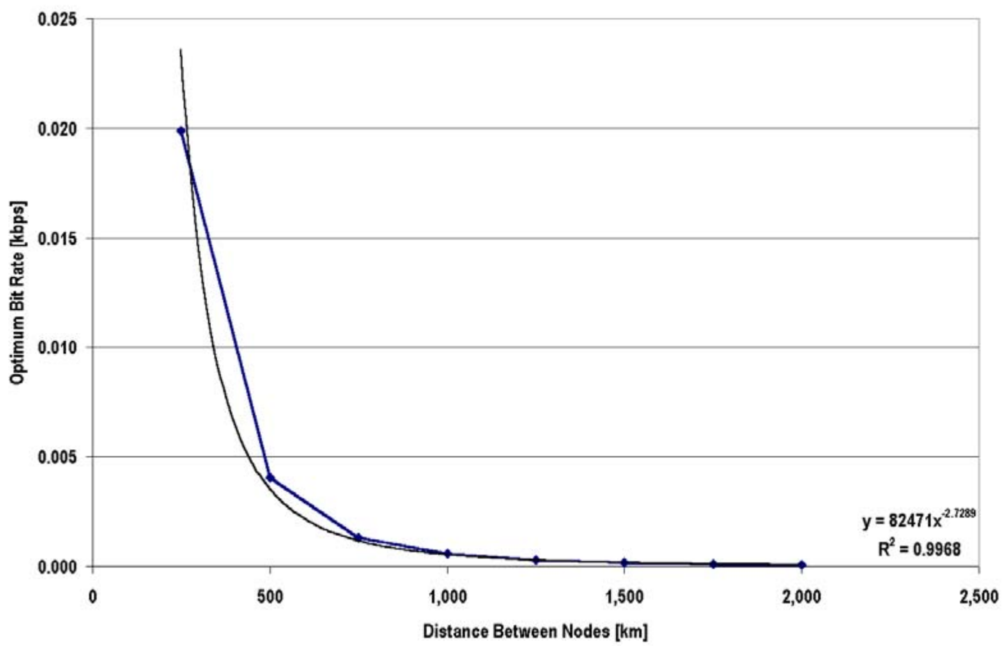

Figure 14. Underdense Trail Bit Rate Sensitivity
(constant bit rate, underdense trail, input antenna power = 200 W, transmit antenna diameter = 1.0 m, receive antenna diameter = 0.5 m, wavelength = 6 m, trail altitude = 75 km)

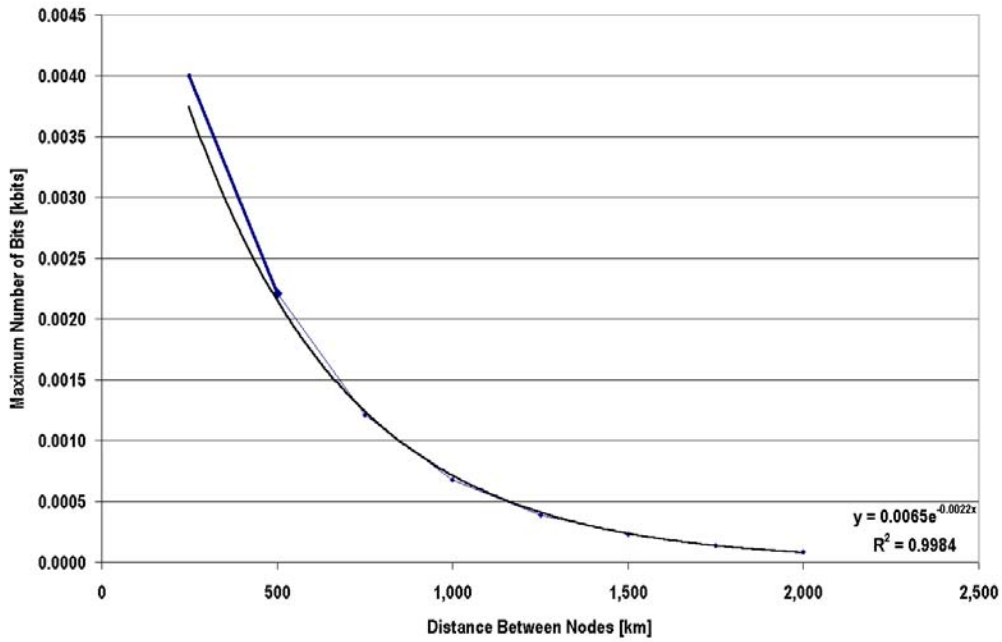

Figure 15. Underdense Trail Number of Bits Sensitivity
(constant bit rate, underdense trail, input antenna power = 200 W, transmit antenna diameter = 1.0 m, receive antenna diameter = 0.5 m, wavelength = 6 m, trail altitude = 75 km)

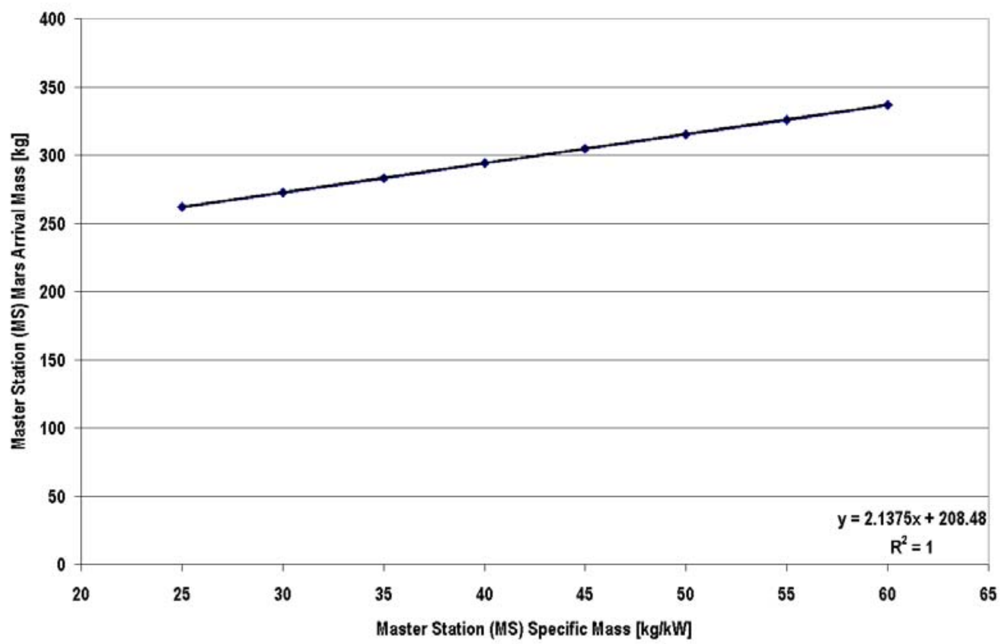

Figure 16. Master Station (MS) Mass Sensitivity
(constant bit rate, underdense trail, distance between nodes = 500 km , input antenna power = 200 W, transmit antenna diameter = 1.0 m, receive antenna diameter = 0.5 m, wavelength = 6 m, trail altitude = 75 km)

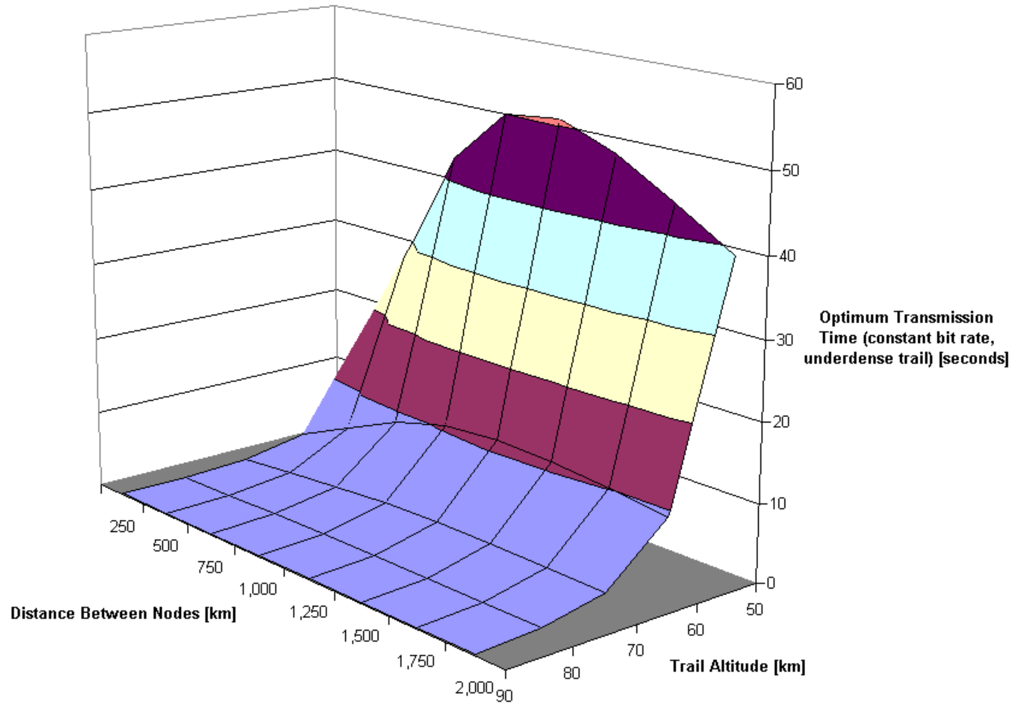

Figure 17. Optimum Transmission Time Versus Meteor Trail Altitude and Distance Between Terminals (constant bit rate, underdense trail, input antenna power = 200 W, transmit antenna diameter = 1.0 m, receive antenna diameter = 0.5 m, wavelength = 6 m)

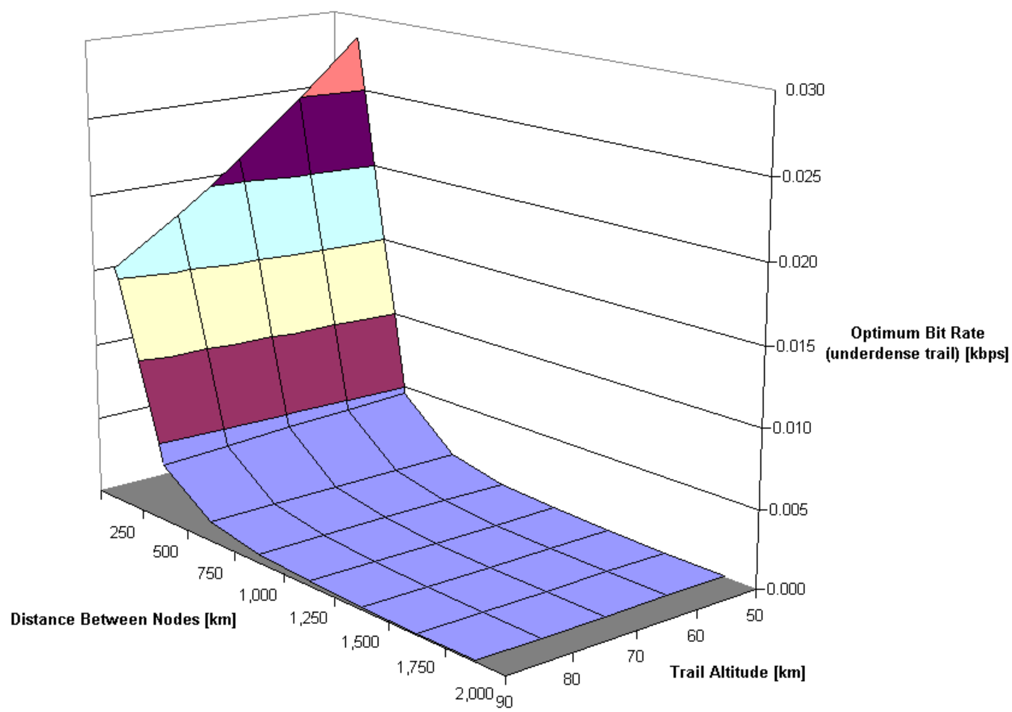

Figure 18. Optimum Bit Rate Versus Meteor Trail Altitude and Distance Between Terminals (constant bit rate, underdense trail, input antenna power = 200 W, transmit antenna diameter = 1.0 m, receive antenna diameter = 0.5 m, wavelength = 6 m)

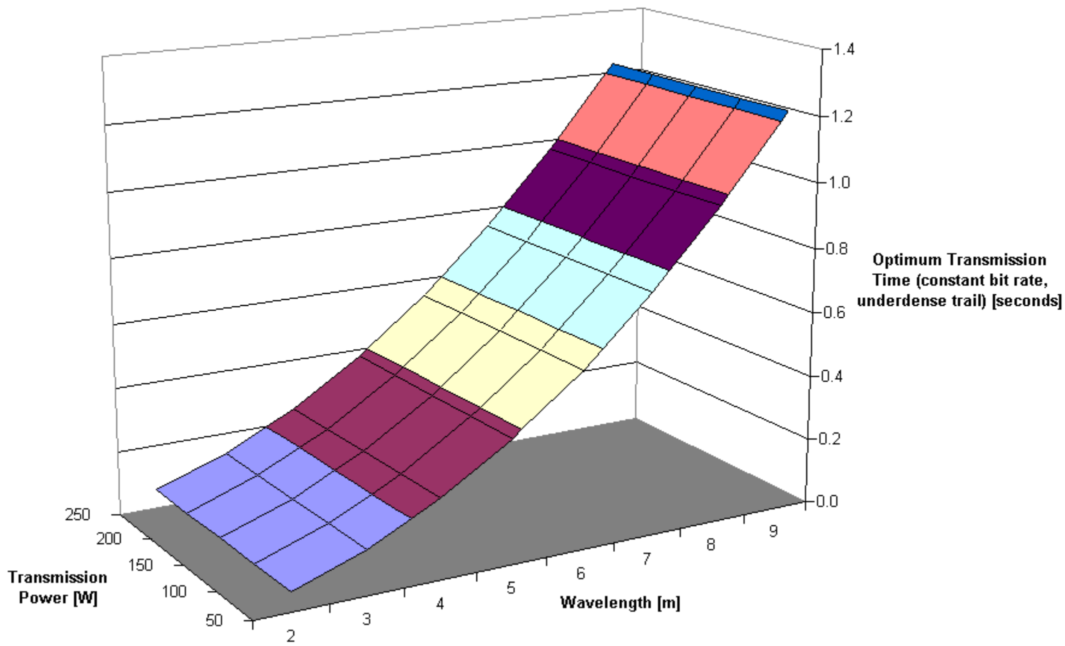

Figure 19. Optimum Transmission Time Versus Wavelength and Transmission Power (constant bit rate, underdense trail, distance between nodes = 500 km, transmit antenna diameter = 1.0 m, receive antenna diameter = 0.5 m, trail altitude = 75 km)

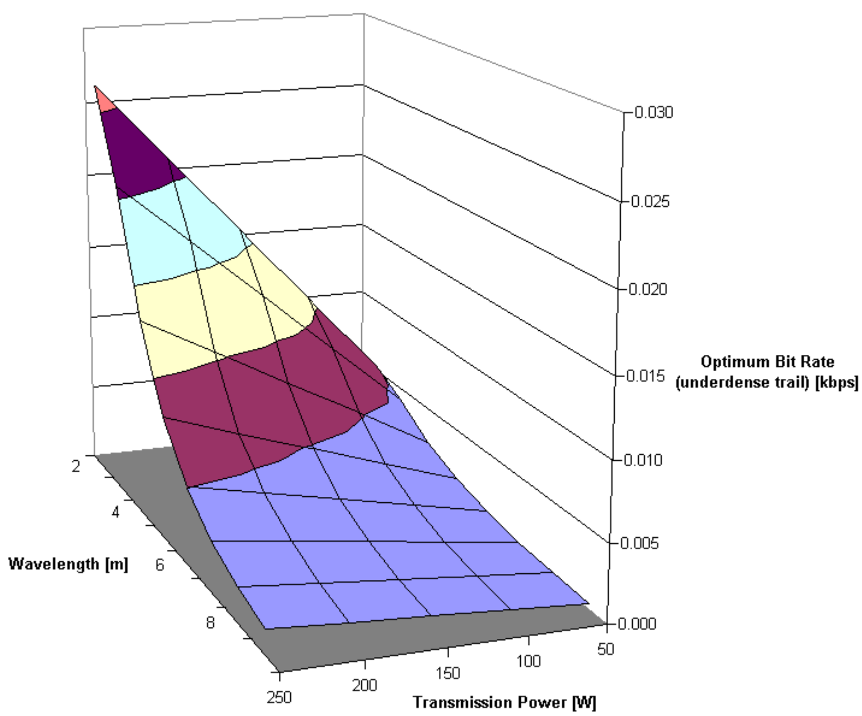

Figure 20. Optimum Bit Rate Versus Wavelength and Transmission Power (constant bit rate, underdense trail, distance between nodes = 500 km, transmit antenna diameter = 1.0 m, receive antenna diameter = 0.5 m, trail altitude = 75 km)

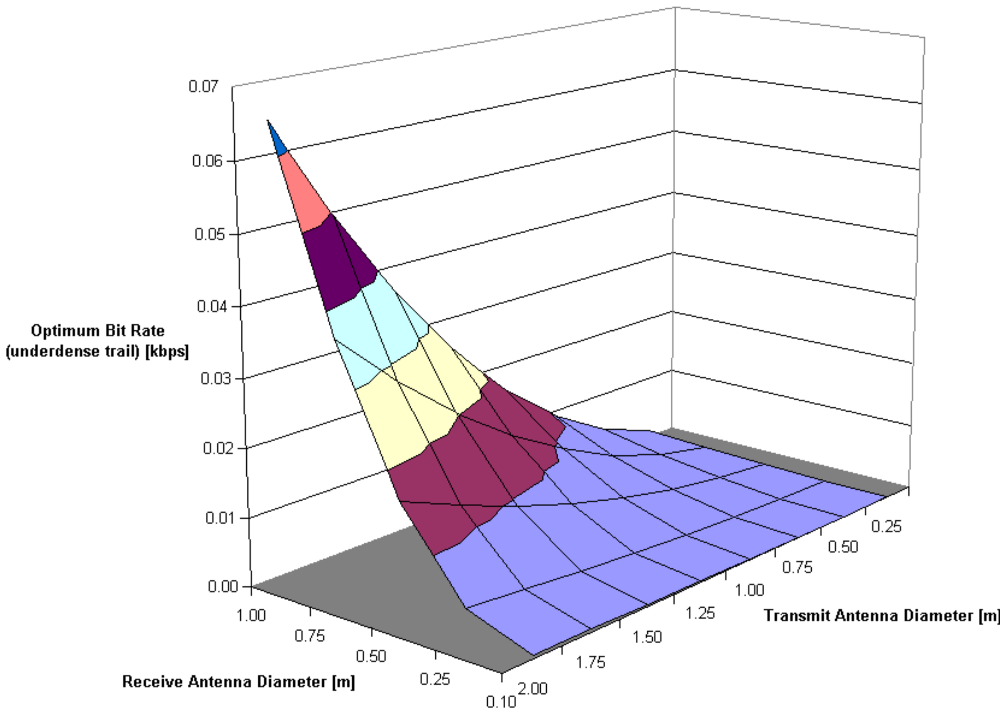

Figure 21. Optimum Bit Rate Versus Transmit Antenna Diameter and Receive Antenna Diameter (constant bit rate, underdense trail, distance between nodes = 500 km, input antenna power = 200 W, wavelength = 6 m, trail altitude = 75 km)

Monte Carlo Simulation Results

Once the ROSETTA model was developed and could be used to deterministically analyze the Martian MB telecommunications architecture, probabilistic design points were calculated in the ModelCenter© environment using the ProbWorks Monte Carlo component (see Figure 22). Distributions were placed upon several relevant system performance parameters (see Table 9). For this examination most of the design variables with distributions were performance oriented. Triangular distributions were placed on the variables since it is often easier to obtain distributions from designers or technologists by asking for low, most likely, and high values versus asking for a specific value of mean and standard deviation (as for a normal distribution). Seven design variables were chosen to have distributions placed upon them with most of these distributions being symmetric around the most likely value. However, some variables including transmission power and station specific mass were skewed towards the lower bound since that would be the direction any technological improvement. Five outputs were chosen to be forecast variables, or those variables whose statistical properties would be measured. One thousand Monte Carlo simulations were performed for this examination with frequency and cumulative distributions generated as well as 90% certainty levels for each of the output parameters.

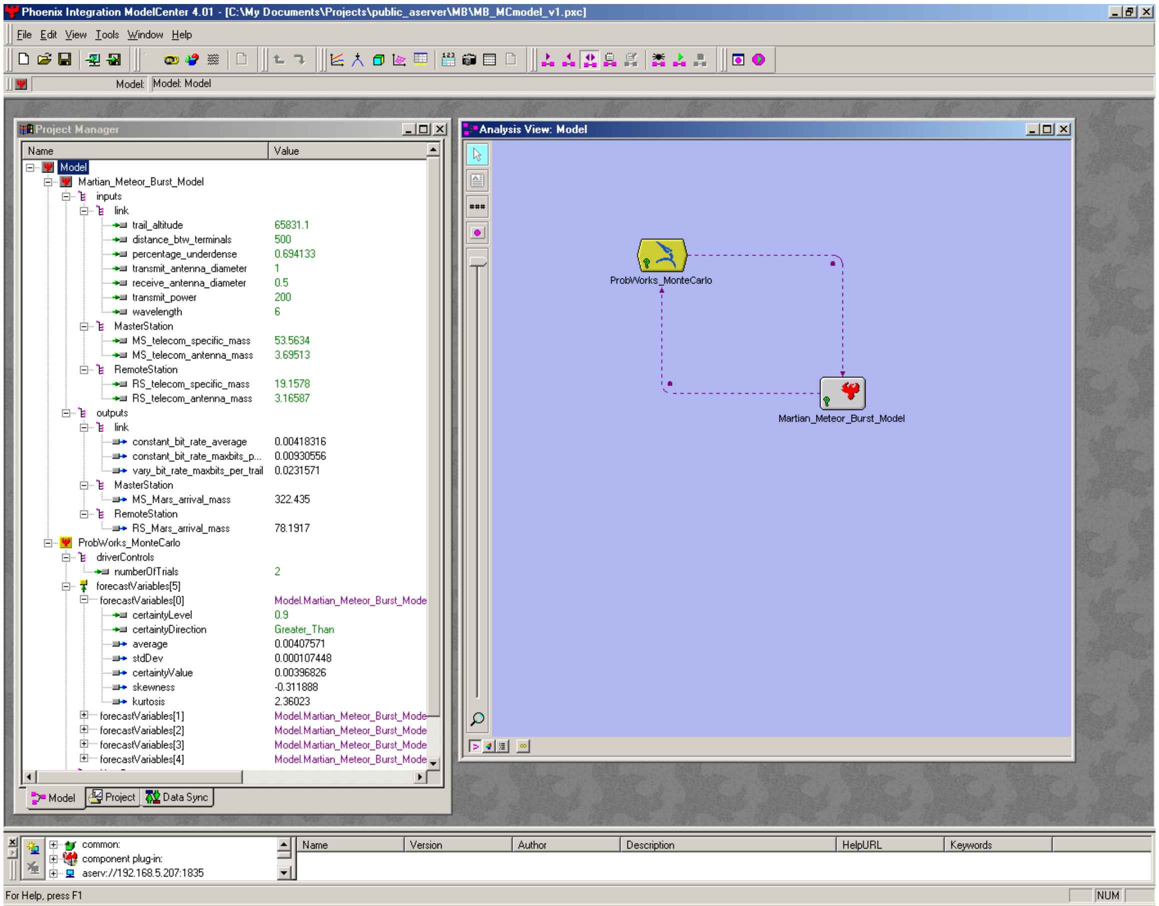

Figure 22. MB ROSETTA Model in ModelCenter© Design Environment and Monte Carlo Component

Table 9. Uncertainty Input Parameters and Associated Triangular Distributions

Uncertainty Parameter	Minimum Value	Most Likely Value	Maximum Value
Transmit power (Master Station) [W]	100	200	200
Trail altitude [km]	50	75	90
Surface distance between terminals/nodes [km]	500	600	700
Master Station (MS) specific mass [kg/kW]	30	56.8	60
Remote Station (RS) specific mass [kg/kW]	10	17.2	20
Transmit antenna diameter [m]	0.8	1	1.2
Receive antenna diameter [m]	0.4	0.5	0.6

As gathered from the previous deterministic analyses, the bit rates for these types of systems on Mars are lower than comparable systems on Earth (see Table 10). Given the uncertainty bounds on the input variables, the 90% certainty levels for some of the output parameters are very low, especially for the constant bit rate where the 90% certainty value is 30% lower than the mean value. Generally the mass of the master station is much larger than that of the remote station, given both its higher specific mass and transmission power level. Figure 23 through 27 display the frequency and cumulative distributions for the 1,000 Monte Carlo simulations.

The shapes of the output probability distributions are related with the input distributions selected. Some of the distributions are heavily skewed, while others are close to being normally distributed.

The distribution for the number of bits parameter is very heavily skewed towards the lower end of the data range. For the data set, the standard deviation is large since sometime larger transmission times occur. Given this the bit rate expected will be in a very narrow range. The mass distributions for the master and remote station are more normally distributed yet with each has a wider spread at the lower range of the data. This effect is correlated with the impact of the specific mass input distribution that was skewed towards the lower end of the distribution.

Table 10. Output Statistical Parameters for Monte Carlo Simulation (1,000 runs)

Uncertainty Parameter	Mean	Standard Deviation	90 % Certainty Level
Bit Rate (constant, underdense trail) [kbps]	0.0035	0.0010	≥ 0.0023
Maximum Number of Bits (constant bit rate, underdense trail) [kbits]	0.0072	0.0132	≥ 0.0007
Maximum Number of Bits (varying bit rate, underdense trail) [kbits]	0.0195	0.0360	≥ 0.0018
Master station (MS) Mars Arrival Mass [kg]	272.0	31.6	≤ 311.1
Remote station (RS) Mars Arrival Mass [kg]	71.4	3.7	≤ 75.8

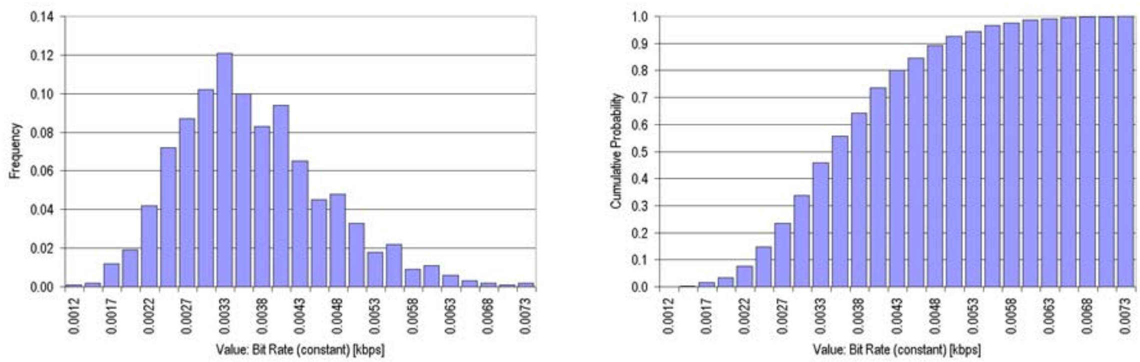

Figure 23. Frequency and Cumulative Distribution: Bit Rate
(constant bit rate, underdense trail, 1000 Monte Carlo simulations)

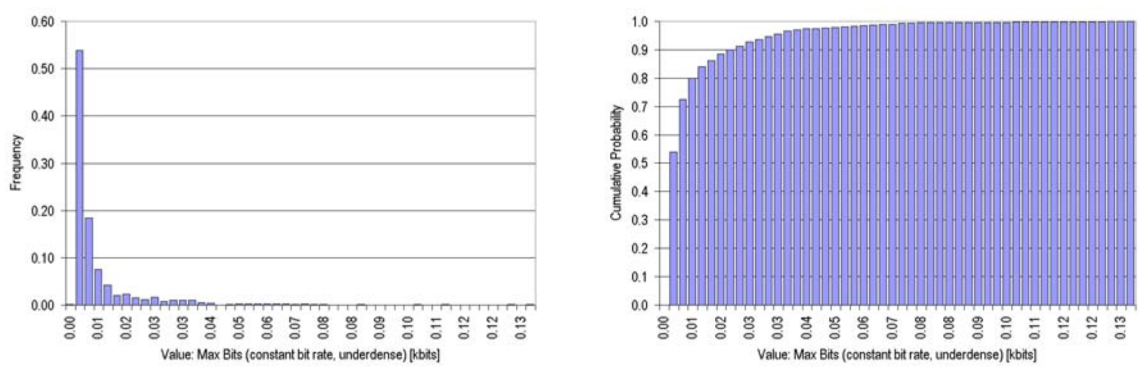

Figure 24. Frequency and Cumulative Distribution: Maximum Number of Bits (Constant Bit Rste)
(constant bit rate, underdense trail, 1000 Monte Carlo simulations)

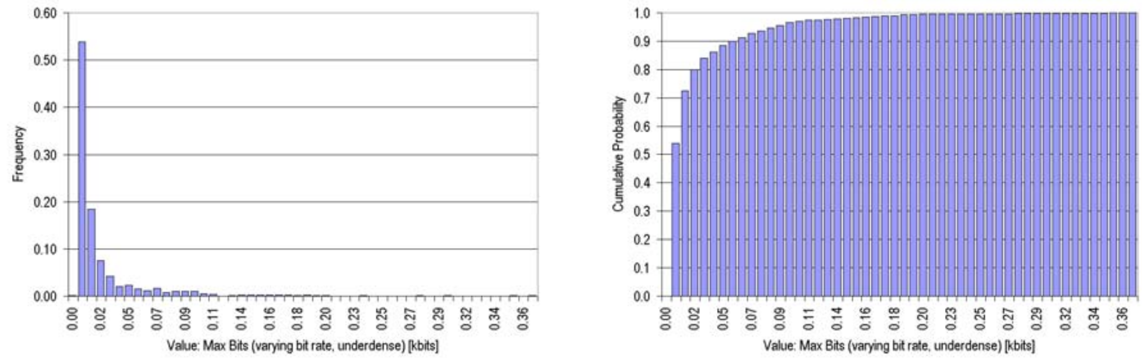

Figure 25. Frequency and Cumulative Distribution: Maximum Number of Bits (Varying Bit Rate) (continuously varying bit rate, underdense trail, 1000 Monte Carlo simulations)

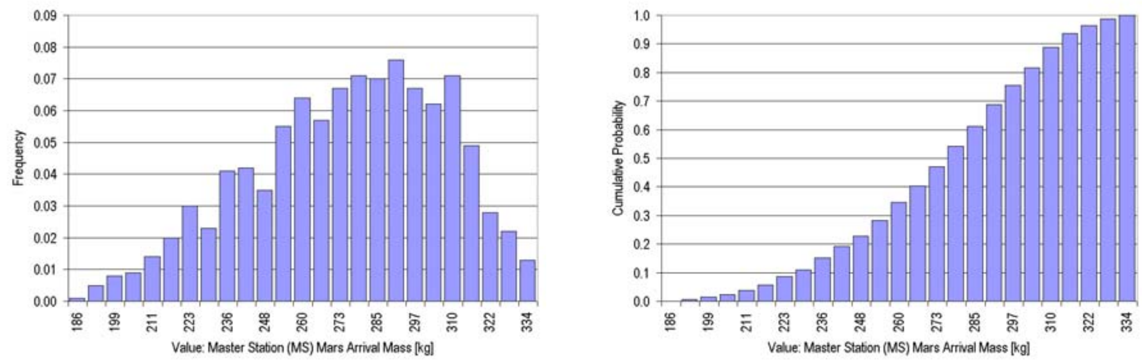

Figure 26. Frequency and Cumulative Distribution: Master Station (MS) Mars Arrival Mass (underdense trail, 1000 Monte Carlo simulations)

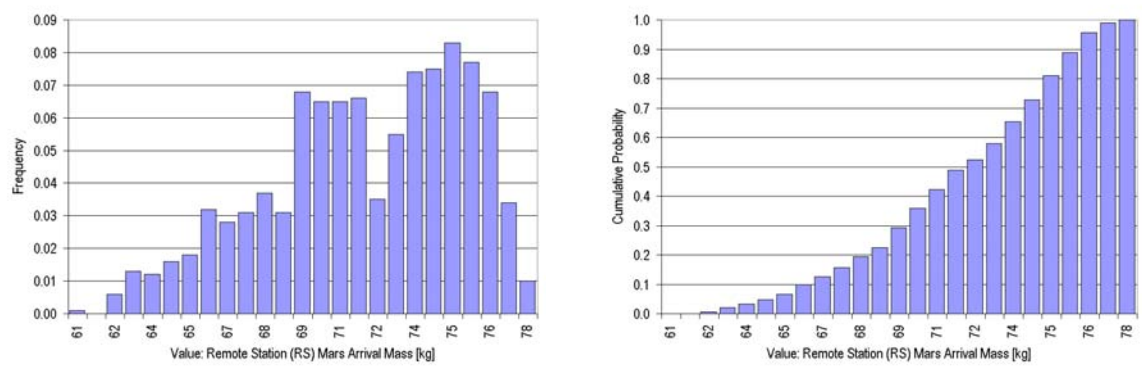

Figure 27. Frequency and Cumulative Distribution: Remote Station (RS) Mars Arrival Mass (underdense trail, 1000 Monte Carlo simulations)

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

Limited, consensus scientific data indicates that atmospheric meteor impacts are similar on Earth and Mars. Generally such impacts could be estimated to occur at similar rates as on Earth. Future exploration spacecraft will provide better data on some of these atmospheric phenomena but perhaps at different particle sizes than those most used for MB communication systems.

These planetary atmospheric impacts could be used for a Martian Meteor Burst (MB) telecommunication system based upon terrestrial technologies and systems. Generally, Martian MB systems will be limited by antenna sizes and transmission power levels available compared to territorial systems. System level modeling, both deterministically and probabilistically, show that data rates for such systems on Mars become relatively unusable after more than 1,000 km separation distance between master and remote stations. Higher power requirements for master stations could lead to non-solar powered options in order to alleviate growth in system mass.

Future examination on this topic could include more detailed analysis of the miniaturization of current MB systems in order to obtain lower telecommunication subsystem specific masses. Additionally, more effects could be accounted for in regards to the effect of the Martian atmosphere on MB links. Strong upper atmosphere winds may distort the meteor trail and possible mitigation effects will have to be investigated. These effects are probably more important for overdense trails.

For the near term, MB systems will have to compete against alternative envisioned architectures such as the Mars Relay Satellite (MRS) with ground stations linked to an orbital satellite through UHF links. These alternate network architectures could enable higher data rates than MB systems for sample missions such as global meteorological and circulation monitoring. However, MB systems seem feasible, yielding lower (compared to terrestrial systems), but still non-trivial data rates for long term monitoring. MB systems could be projected not as the primary telecommunications network of choice on Mars but acting as a backup architecture to benefit global Mars-centric communication.

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APPENDIX B: WEB SITES

www.meteorcomm.com
Homepage of commercial company Meteor Communications Corporation (MCC) based in Kent, Washington.

www.starcomwireless.com
Homepage of commercial company StarCom Wireless based in Bellingham, Washington.

www.warnmonitor.com
Homepage of commercial company Warning & Monitoring Systems International (WMSI) which is a partnership between BC Hydro International (BCHIL) and Meteor Communications Corporation (MCC).

members.tripod.com/faza1/mbcont.htm
This website provides a very general overview of terrestrial Meteor Burst operation and technology.

www.radio.gov.uk/topics/research/rtcg/projects/project576.pdf
A report from the Radio Technology and Compatibility Group (RTCG) at Whyteleafe in the U.K.. Report title: Project Number 576: "39 MHz Mobile Meteor Burst Communications / TV (I.F.) Compatibility", project manager John Mellish.

www.amsmeteors.org/radmet.html
Introductory article and faq about radio meteor scatter, specifically tailored to radio enthusiasts, from the American Meteor Society, Ltd.

www.polar.umd.edu/mars/mars_report.html
Report from the Space & Upper Atmospheric Physics research group at the University of Maryland of Lunar and Planetary Institute, Tech. Rep. 95-xx, Part 6: "Atmospheres From Within".

www.imo.net
International Meteor Organization (IMO)

www.spaceweather.com/glossary/nasameteorradar.html
NASA Marshall Space Flight Center (MSFC) online meteor radar

APPENDIX C: TERRESTRIAL METEOR BURST (MB) TECHNOLOGY

METEOR BURST (MB) MASTER STATION (MS)

Transmitter Power out: 250-10,000 W
Frequency: 40-50 Mhz
Size: 0.91 m Height x 0.81 m Depth x 0.56 m Width
Weight: 90.7 kg

MCC-520B/C
Meteor Burst Master Station
Meteor Communications Corporation (MCC)

Transmitter Power out: 200 W
Frequency: 40-50 Mhz
Size: 0.43 m Height x 0.53 m Depth x.0.17 m Width
Weight: 11.3 kg

MCC-525
Meteor Burst Mini-Master Station
Meteor Communications Corporation (MCC)

METEOR BURST (MB) REMOTE STATION (RS)

Transmitter Power out: 100 W
Frequency: 40-50 Mhz
Size: 0.28 m Height x 0.33 m Depth x 0.09 m Width
Weight: 5.4 kg

MCC-550C Remote Terminal
Meteor Burst Remote Station
Meteor Communications Corporation (MCC)

APPENDIX D: ORGANIZATIONS AND PERSONNEL

INVESTIGATING ORGANIZATION: SPACEWORKS ENGINEERING, INC. (SEI)

SpaceWorks Engineering, Inc. (SEI) is here to examine the imagined future with real tools. SEI can provide consul to those seeking to exploit outer space, from transportation to infrastructure, for public and private, from science to tourism. The firm's conceptual level toolsets and method can help determine feasibilities of space systems, viabilities in the marketplace, and determine the temporal impacts of technology on public and private actors. The firm also forecasts future markets making determinations of future policy and media initiatives. Founded by Dr. John R. Olds, SEI is a small aerospace engineering and consulting company located in metro Atlanta. The firm specializes in providing timely and unbiased analysis of advanced space concepts ranging from space launch vehicles to deep space missions. The firm's practice areas include:

- Space Systems Analysis
    - Conceptual Level Engineering Analysis
    - Conceptual Level Engineering Design
    - Life Cycle Assessment
    - Cost Engineering
    - Advanced / Robust Design Processes

Space Systems Analysis is central to SEI's capabilities. Our quick-response, conceptual-level analysis of advanced space transportation concepts includes both technical and programmatic assessments using industry-standard tools and methods. Technical assessments cover concept weights, propulsion, CAD drawings, aerodynamics, thermal protection requirements, etc. Programmatic assessments cover non-recurring costs, recurring costs, operations costs, fleet production requirements, turnaround time estimates, and safety and reliability assessments. SEI can perform both traditional deterministic and probabilistic analyses to explicitly evaluate risk through uncertainty in key design variables. Key to our success is our focus on providing timely, unbiased, and independent systems analysis for government and commercial customers.

- Technology Prioritization
    - Technology Anticipation
    - Technology Benefit Assessments
    - Technology Prioritization

Technology development budgets are tight in not only the space industry but throughout the economy, so strategic decision-makers in government and industry are forced to make tough choices to direct scarce resources. Decision-makers need inexpensive, timely, analytical, and robust methodologies for prioritization of advanced technology investment. SEI specializes in performing focused and speculative technology benefit-to-cost assessments. For example, a customer might want to know what threshold of improvement a new propulsion or material technology must achieve in order to produce a desired weight or cost benefit to the entire transportation system. SEI can perform both traditional deterministic and probabilistic analyses to explicitly evaluate risk through uncertainty in key design variables.

- Financial Engineering
    - Business Design
    - Future Venture Due Diligence
    - Real Options Analysis

Given limited resources of future public outlays in space, future long-term space activities will necessarily involve the commercial sector. In this environment, economic viability will overwhelm technical feasibility as the key driver in space system development decisions. SEI has the capability to examine space projects, both near and far term, using rigorous financial evaluation instruments. SEI can help determine the business case and break-even points for various candidate space transportation and infrastructure projects.

- Future Market Assessment
    - Scenario Planning
    - Market Forecasting
    - Market Analysis

Public and private entities have different priorities for space services, which lead to different demand curves. Changing space markets will only enhance these differences in the future. SEI combines its scenario visioning capabilities with the best forecasts available to provide clients with guidance on how markets will grow and evolve through the middle of this century, from current terrestrial telecommunication markets to future cis-lunar resource markets to Space Solar Power. SEI's strategic vision in this area is to help navigate the minefield of wild predictions and dire warnings to obtain clarity as to the shape of the future demand curve.

- Policy and Media Consultation
    - Government Initiatives
    - Policy Consultation
    - Television, Film, Radio, Internet Presence

It has been more than forty years since the dawn of the space age, and the notion of human spaceflight has settled comfortably into the human psyche. Still, current government policies affecting space are critical to the success of future commercial space activities and will require continued reevaluation and adjustment as the industry matures. Also, the entertainment industry and media[1]s understanding of space affects its characterization of our future, which in turn impacts the level of support in the general populace. SEI believes it is vital for both policy makers and the media to have accurate and up-to-date technical information, so we are dedicated to providing our expertise to non-technical persons.

The firm's capabilities include conceptual level modeling of a broad range of future space transportation and infrastructure concepts. Typical systems architectures might include 2nd/ 3rd / 4th generation single-stage and two-stage reusable launch vehicle designs (rocket, airbreather, combined-cycle), launch assist systems, in-space transfer vehicles and upper stages, orbital maneuvering vehicles, lunar and Mars transfer vehicles for human exploration missions, in-space transportation nodes and propellant depots, and interstellar missions. For these and other concepts, SEI can provide complete packaged analyses, from the initial vision to a final converged engineering concept, including: engineering design and analysis, independent concept assessment, life cycle analysis, and programmatic and technical analysis. SEI can perform both deterministic analyses and probabilistic analyses that explicitly evaluate risk through uncertainty in key design variables. SEI has experience with many industry standard conceptual aerospace engineering disciplinary analysis tools.

PRINCIPAL INVESTIGATOR (PI): A.C. CHARANIA

Mr. A.C. Charania is senior futurist at SpaceWorks Engineering, Inc. (SEI). His previous experience includes roles at Accenture (formerly Andersen Consulting), Futron Corporation, and Georgia

Institute of Technology's Space Systems Design Laboratory (SSDL). At the first organization, projects involved formulating strategies to address future concepts of the "network" as applied to comprehensive strategic technology assessments of the terrestrial telecommunications marketplace; examining both markets (long distance, local access, Internet, Intranet, and E-Commerce) and technologies (ATM, AIN, ISDN, and xDSL). Projects at the latter two organizations included conceptual design and analysis (with a concentration on financial engineering and robust design) of future space concepts such as: Space Solar Power for NASA Marshall, Mars Orbit Basing (MOB) / Solar Clipper for NASA HQ, 3rd Gen and Bantam RLVs for NASA Marshall, space tourism for NASA Langley, Phobos landers, and Europa landers. In particular, his expertise includes far term technology / market forecasting utilizing analytical models and incorporation of robust design methods in the conceptual design process. He holds an M.S. in Aerospace Engineering from the Georgia Institute of Technology (with a concentration in systems design and optimization), a B.S. in Aerospace Engineering from the Georgia Institute of Technology, and a B.A. in Economics/Mathematics from Emory University.

ASSISTING ORGANIZATION: METEOR COMMUNICATIONS CORPORATION (MCC)

Based in Kent, Washington, Meteor Communications Corporation (MCC) is an employee owned company that designs, manufactures and markets wireless information systems for use in military and commercial applications. MCC's military business emerged from its research and development work for the United States government in the late 1970s. These development programs have led to a number of defense related procurements for special purpose defense communications systems. The technology developed for the government formed the basis for the turnkey digital packet radio networks MCC is presently marketing for both government and commercial applications around the world.

The company is the world leader in meteor burst communication technology. The earliest known study of meteor trail propagation of radio signals began in the early 1930s. The techniques of using these trails for communication can be attributed to ham radio operators who, under certain conditions, found themselves communicating hundreds of miles further than normally possible on VHF frequencies. Interest in meteor burst continued into the 1950s when intensive research began and the National Bureau of Standards, Stanford Research Institute, North Atlantic Treaty Organization, and the Canadian Defense Research Board all built systems to evaluate the technique. However, it was not until MCC successfully integrated high-speed microprocessor-based computer equipment into the systems in 1975, that meteor burst communications became a functional reality in data communications. MCC, using advanced computer technology and the world's leading engineers in meteor and radio communications, perfected the necessary antennae, created software and reinvented the equipment to transfer meteor burst into a reliable, efficient method of transmitting digital information. MCC is the only company in the world capable of successfully designing and implementing meteor burst technology into turnkey digital communications networks at this time. Since the company was founded in 1975, over fifty million dollars ($50M) has been spent on R&D. An important spin-off has been the development of wide area networks for mobile data communications. These networks now comprise about one half of the company's revenues and will contribute significantly to the company's future growth. MCC has been granted two nationwide frequencies by the FCC to operate a national mobile data service and two nationwide frequencies for stationary data transmission. In addition, MCC has frequencies for use in Alaska, Hawaii, Puerto Rico, and in the United Kingdom. MCC has been granted technology patents and is actively engaged in research and development for future compatible use patents.

CONSULTANT: DALE K. SMITH

Mr. Dale K. Smith is one of five partners who founded Meteor Communications Corporation (MCC) in 1975. He originally served on the MCC board of directors as corporate secretary. He served as MCC's data systems manager for 11 years, since the company's founding. Mr. Smith currently supervises MCC's test and evaluation group, as well as participating in MCC system design, which includes his responsibility for the development of all meteor burst link protocols. Mr. Smith has been responsible for all MCC software products, starting with the SNOTEL system, and including every major contract MCC has held. He has also been involved in the design and development of all MCC meteor burst systems, including the latest 6560 Master Station communications networks. Mr. Smith holds two patents in meteor burst link protocols. Mr. Smith was introduced to meteor burst communications at Boeing in 1970 when he designed a fixed logic meteor burst link. This effort was very successful and led to several other test links at Boeing. These follow-on projects included the first computer-controlled link, long message capability (using message piecing), a data acquisition link, and a point-to-point full-duplex link. Mr. Smith's other projects at Boeing dealt with computer and systems interfaces and hardware/software interfaces. He was one of three engineers who designed and developed one of the first digital Attitude Control Computers for satellite attitude control. In addition, Mr. Smith developed a digital data recorder system for recording incoming data and outputting it to a microwave link; he also designed a digital display refresh unit for CRT image generation and refresh. Mr. Smith holds an M.S. in Electrical Engineering from the University of Washington (1972), a B.S. in Electrical Engineering from University of Illinois (1967)

APPENDIX E: PRODUCTION NOTES

CREDITS

This report was conceived and started by SpaceWorks Engineering, Inc. (SEI) with most major portions originating from the firm and specifically the lead author.

PRODUCTION NOTES

This document was created electronically using Microsoft Word for Office 2000, Microsoft PowerPoint for Office 2000, and Adobe Acrobat. Graphic art was produced using Adobe Photoshop and Denaba Canvas. Times Roman, Arial, Arial Narrow, Arial Black, and Arial Unicode MS typefaces are used throughout this document.