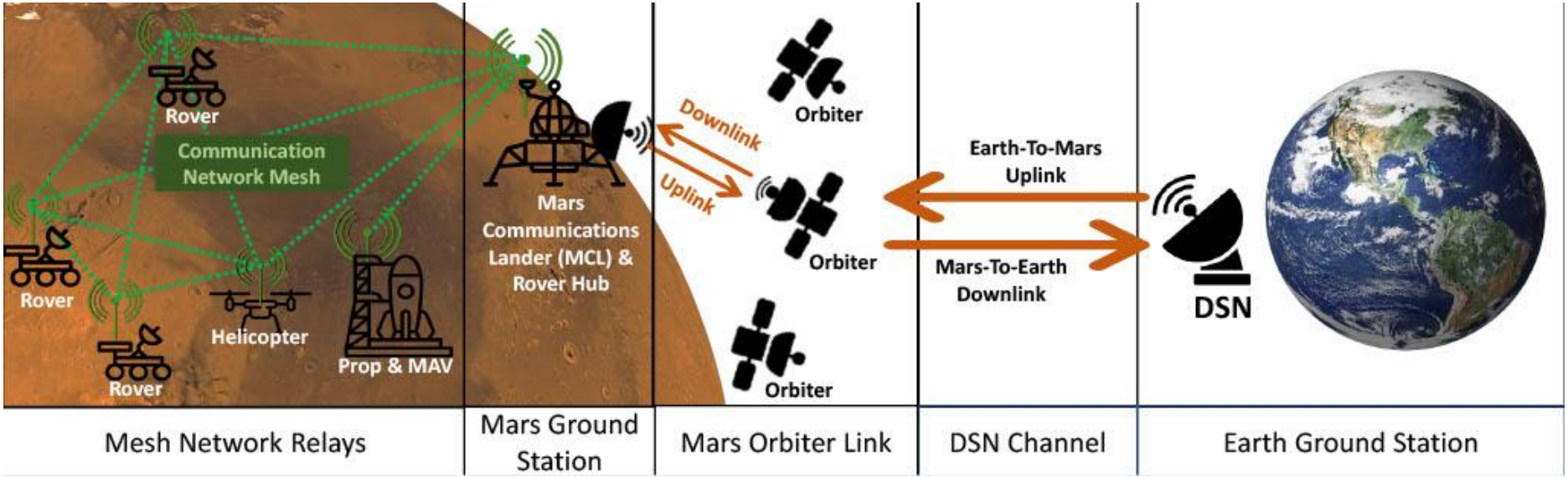
Communications

Julianne Miana, Tamara Hinderman

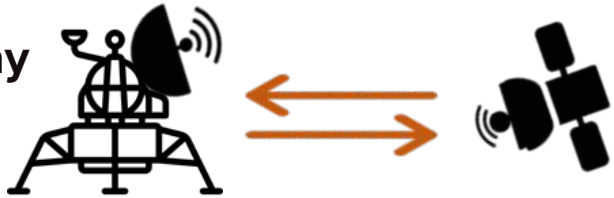
ID	Requirements
COMM-1	Mars orbiters shall maintain radio frequency or optical communications within all communication links (both Earth and Mars ground stations) with a **maximum BER of 10e-6** and a minimum **link margin of 3 dB**.
COMM-2	Mars orbiters shall maintain radio frequency or optical communications with both Earth and Mars at a data rate of at **least 100 kbps**
COMM-3	MATER communications with both Earth and Mars ground stations shall maintain a minimum transmission of **1 relay per hour within every 24 hour period on Mars**

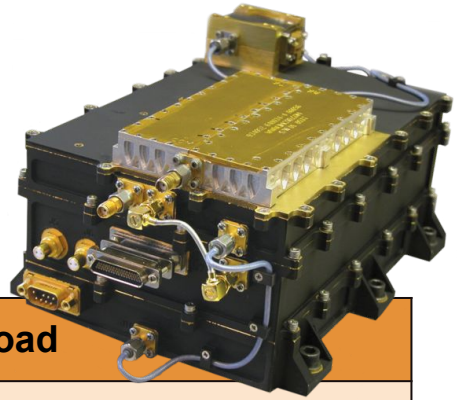
High-Level Architecture



Lander - Orbiter Link Specifications

3 orbiters will add to 5 Mars Relay Network (MRN) orbiters





Hardware

- UHF Electra transceiver radio with a low-gain antenna
  - Half-duplex, BPSK
- Flight heritage: MRN orbiters

Software & Data Handling

- Proximity-1 Space Link Protocol
- Forward and Return

SWaP	Electra Payload
Size [cm]	Transceiver: 21.7 cm x 20.1 cm x 12.2 cm LGA: 26.1 cm dia x 30.5 cm
Weight/mass [kg]	6.5 kg
Power [W]	77.8 W max
Quantity	2 per orbiter & lander

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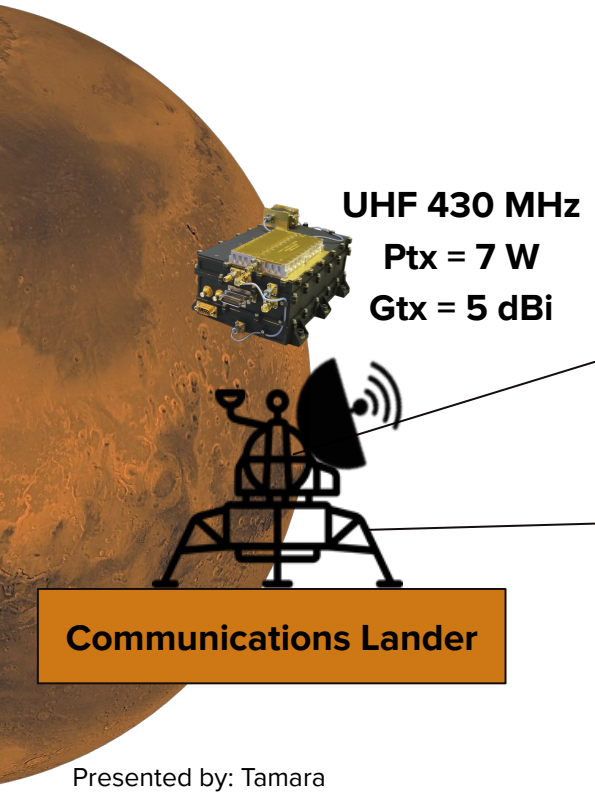
Contributors to Content: Julianne

Lander - Orbiter Link



UHF 430 MHz
Ptx = 7 W
Gtx = 5 dBi

~17000 km

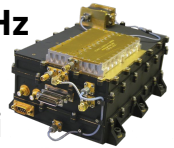
MATER Orbiter
AEO

UHF 430 MHz
Ptx = 7 W
Gtx = 5 dBi

~400-800 km

MATER Orbiter
LMO

UHF 430 MHz
Ptx = 7 W
Gtx = 5 dBi



Communications Lander

****Orbits and distances not to scale**

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Contributors to Content: Tamara, Julianne

Lander - Orbiter Link
UPLINK

Communications Lander

~400-800 km

Success

BER(BPSK): 1.09E-29

Data rate : 542 kbps-1.2 Mbps

MATER Orbiter

LMO

~17000 km

Success

BER (BPSK): 1.36E-19

Data rate : 2.7 kbps

MATER Orbiter

AEO

****Orbits and distances not to scale**

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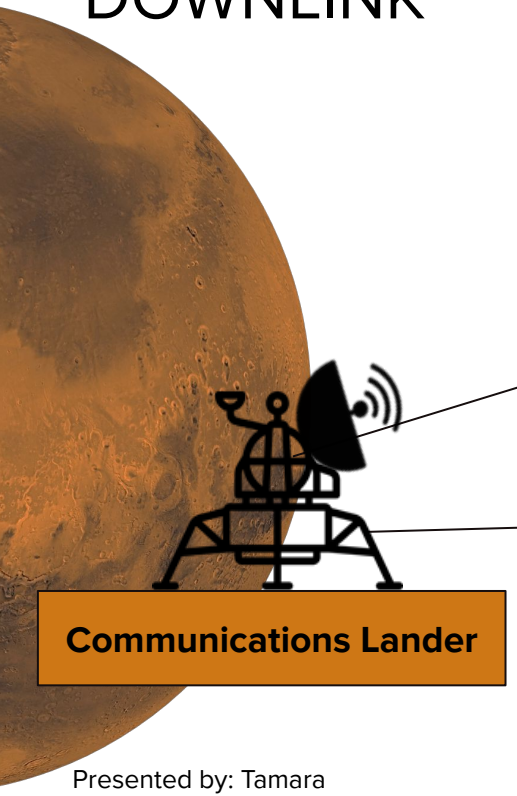
Lander - Orbiter Link
DOWNLINK



MATER Orbiter
AEO

BER (BPSK): 4.2E-21
Data rate : 5.96 kbps

Success

~17000 km

~400-800 km

MATER Orbiter
LMO

Success

BER (BPSK): 3.41E-31
Data rate : 1.19 Mbps - 2 Mbps

Communications Lander

****Orbits and distances not to scale**

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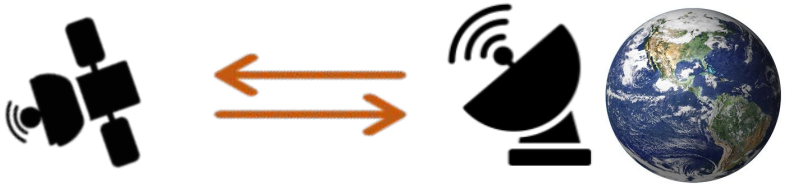
Contributors to Content: Tamara, Julianne

Orbiter-DSN Link

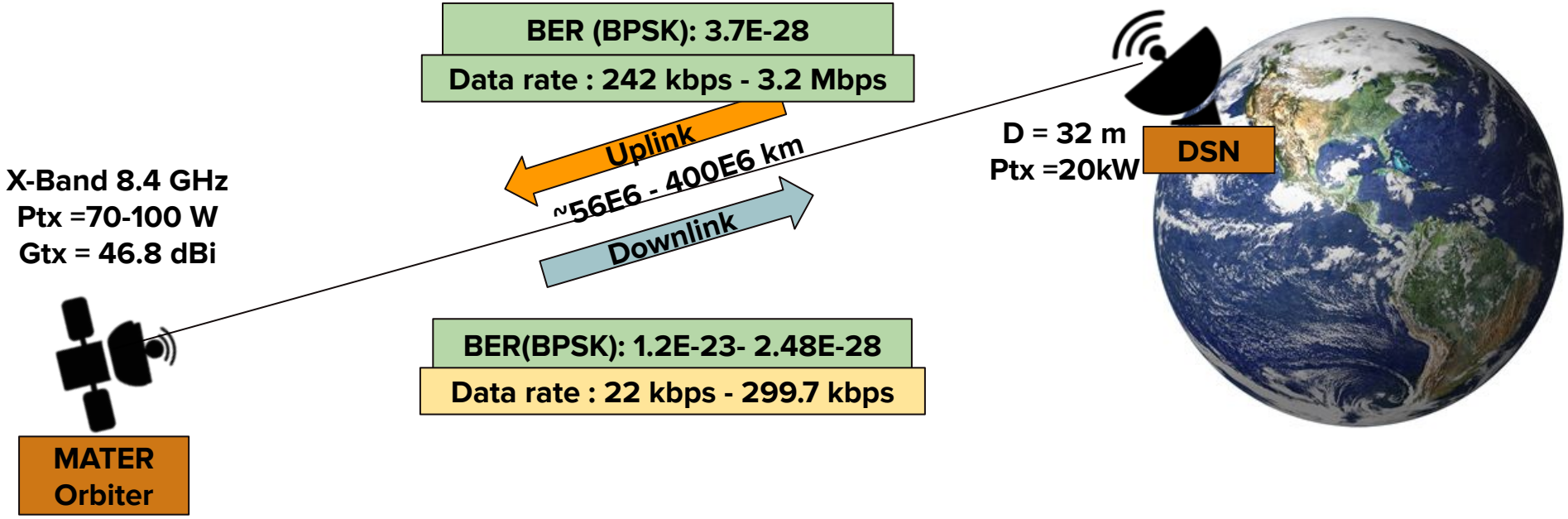
Hardware
- X-band radio, 2 m high-gain antenna (HGA), 100 W traveling wave tube amplifier (TWTA)
- Flight heritage: ESA Trace Gas Orbiter (TGO)

Software
- Store and forward protocol
- Flight heritage: Mars Reconnaissance Orbiter (MRO)



SWaP	X-band Radio System
Size [cm]	SDST: 18.11 cm x 16.64 cm x 11.43 cm HGA: 200 cm dia
Weight/mass [kg]	66.3 kg
Power [W]	290.74 W max
Quantity	1 per orbiter

Orbiter-Earth Link



**Orbits and distances not to scale

Optical vs RF Trade Study

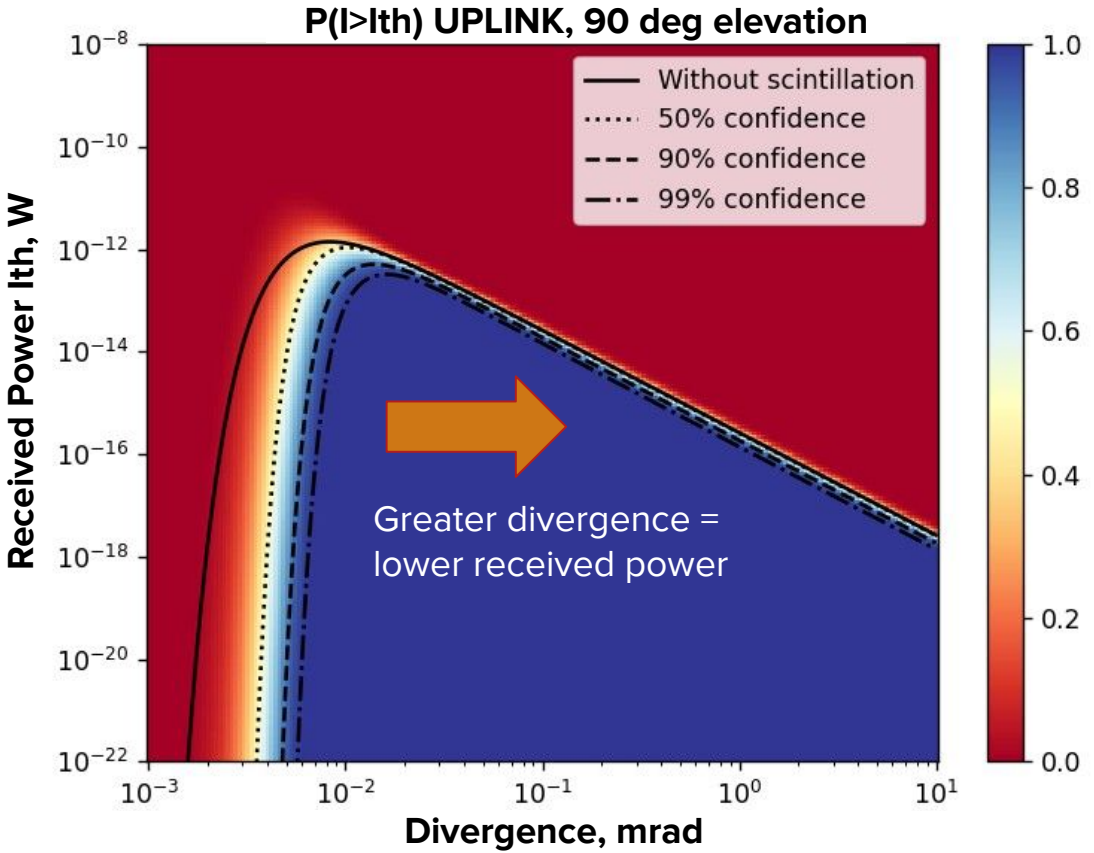
Lasercom

ADVANTAGES

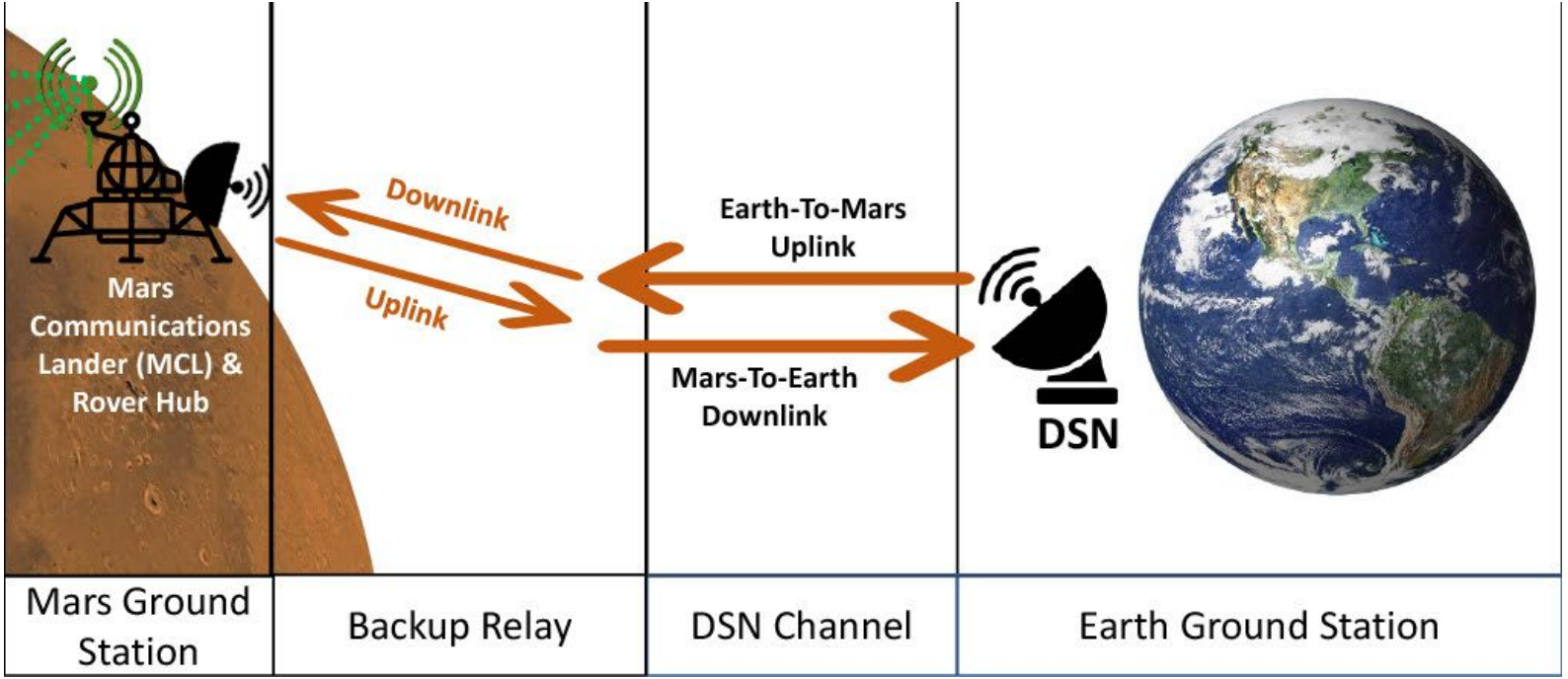
- **High data rates: 2-18 Mbps using SNSPD**
- No interference

DISADVANTAGES

- **Requires high pointing accuracy & divergence**
- Severe atmospheric attenuation
- SWaP payload increase
- Incompatibility with current MRO orbiters



Backup link from Surface to DSN



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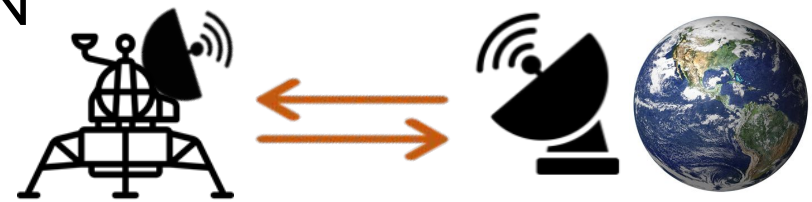
Backup link from Surface to DSN



Hardware

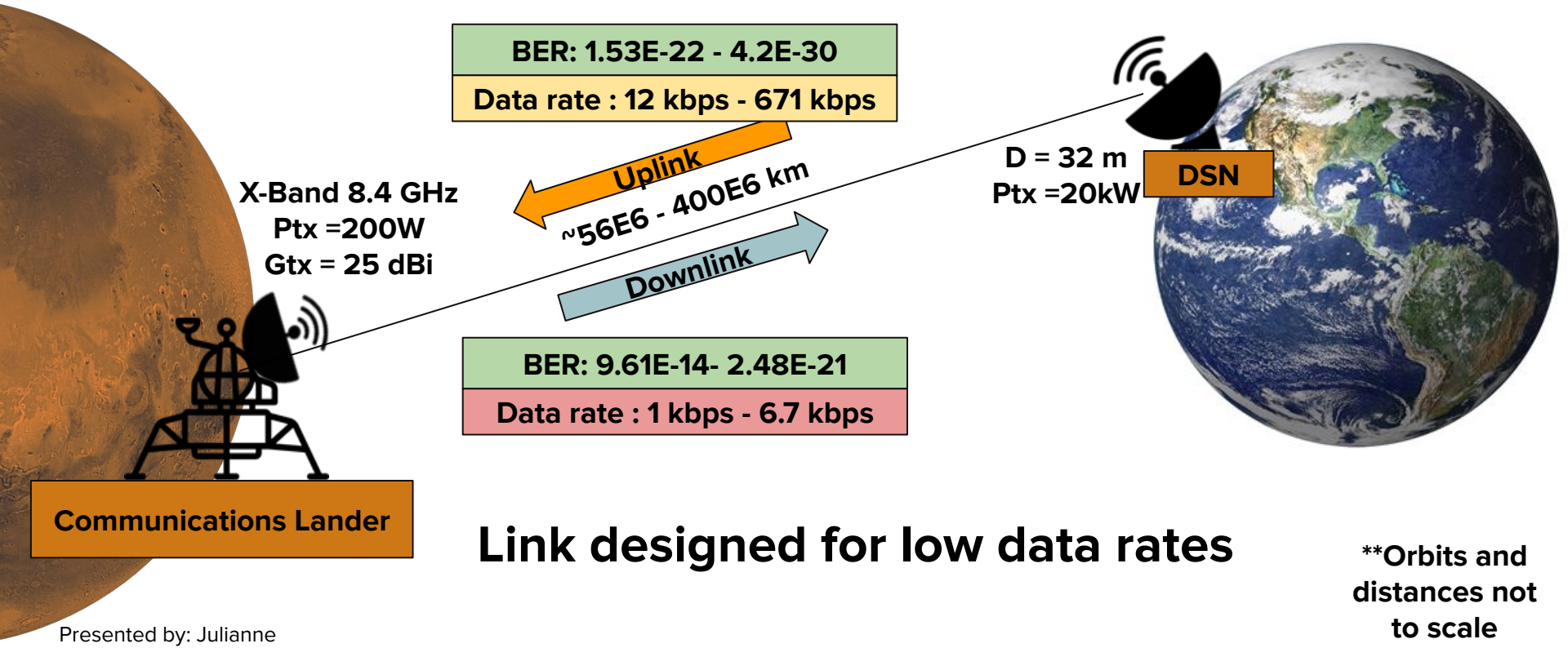
- X-band radio system with a solid-state power amplifier (SSPA), HGA, LGA
- Flight Heritage: Mars rovers (e.g. Curiosity, Opportunity)

Software

- Backup protocol
- Emergency protocol

SWaP	X-band Radio System
Size [cm]	SDST: 18.11 cm x 16.64 cm x 11.43 cm SSPA: 17.4 cm x 13.4 cm x 4.7 cm HGA: 30 cm dia x 29.4 cm LGA: 60.2 cm x 3.1 cm
Weight/mass [kg]	18.94 kg
Power [W]	71.8 W max
Quantity	1 on Lander

Backup link from Surface to DSN



Link designed for low data rates

**Orbits and distances not to scale

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Contributors to Content: Tamara, Julianne

Surface Comms

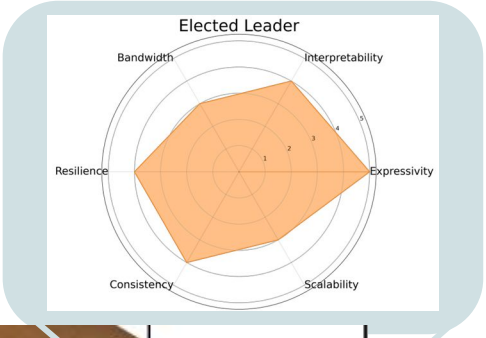
Mesh network to manage surface communication

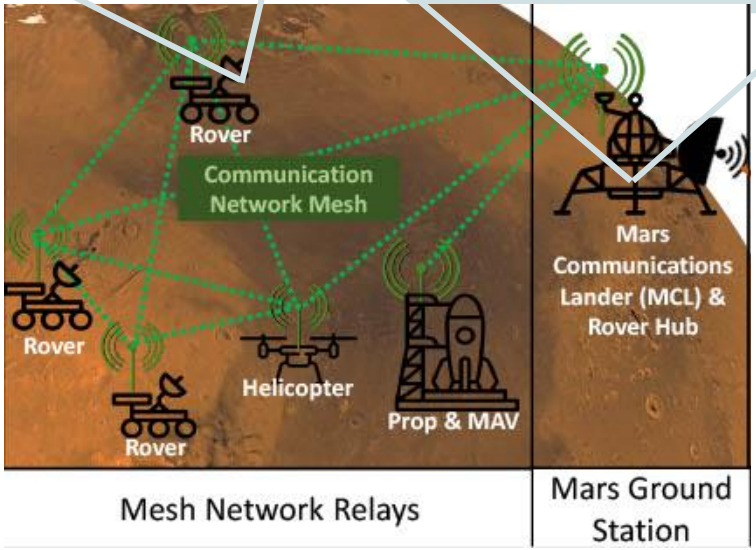
Hardware

- COTS mesh radios (UWB or UHF)
- Flight heritage: CADRE mission (A-PUFFER robots)

Software

- Wireless mesh communication protocol
- TDMA, peer-to-peer topology





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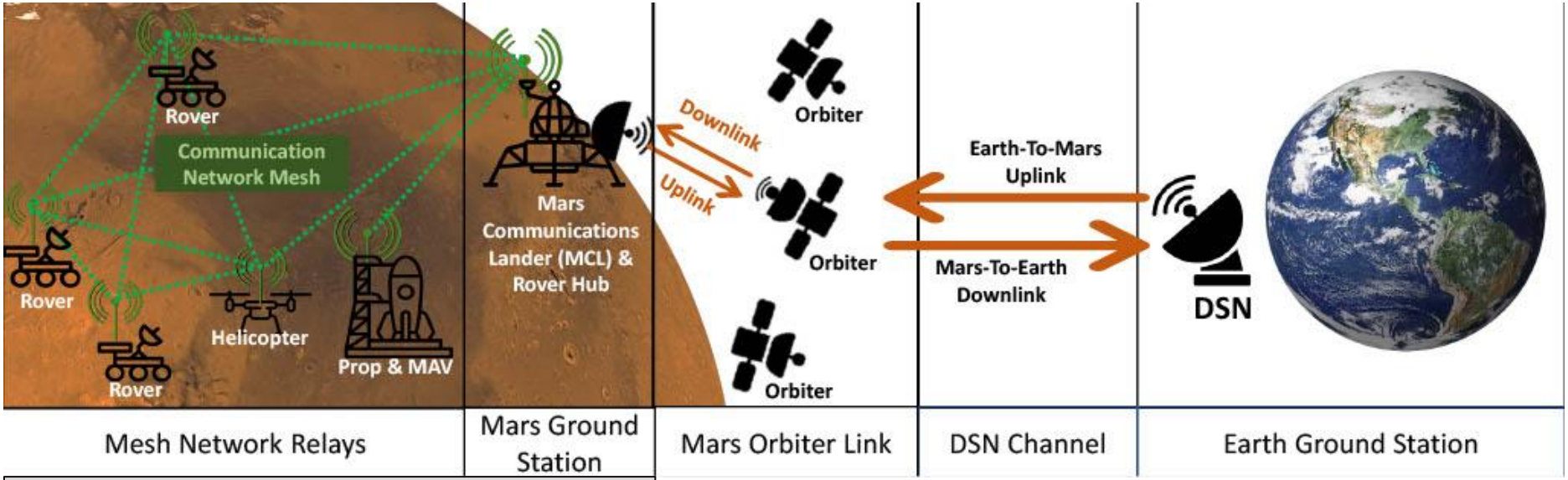
Contributors to Content: Tamara, Julianne

Key Takeaways



MeshNet- To Be Completed

LMO Link - Successful

AEO Link - Needs Work

Orbiter, DSN Link - Partial Success

Lander, DSN Link - Backup Low Data Rate

Presented by: Tamara
Contributors to Content: Tamara, Julianne

Comms Backup Slides

Citations

[1] de la Croix, J.-P., Rossi, F., Brockers, R., Aguilar, D., Albee, K., Boroson, E., Cauligi, A., Delaune, J., Hewitt, R., Kogan, D., Lim, G., Morrell, B., Nakka, Y., Nguyen, V., Proença, P., Rabideau, G., Russino, J., da Silva, M. S., Zohar, G., and Comandur, S., "Multi-Agent Autonomy for Space Exploration on the CADRE Lunar Technology Demonstration," 2024 IEEE Aerospace Conference, 2024, pp. 1–14. https://doi.org/10.1109/AERO58975.2024.10521425.
[2] NASA, "Electra Mars Proximity-Link Communications and Navigation Payload Description," Mars Exploration Program, 2009.
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[11] Taylor, J., Lee, D., and Shambayati, S., "Chapter 6 - Mars Reconnaissance Orbiter," Deep Space Communications, 2014.
[12] de la Croix, J.-P., and Rossi, F., "Multi-Agent Autonomy for Space Exploration," , 2024. URL https://ai.jpl.nasa.gov/public/documents/presentations/CADRE-AAMAS-Slides.pdf.
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[14] Elder, X., "Configuring and Testing Mesh Radios for Air-To-Ground Communications," , 2024. URL https://ntrs.nasa.gov/api/citations/20240010247/downloads/Configuring%20and%20Testing%20Mesh%20Radios-Final.pdf.
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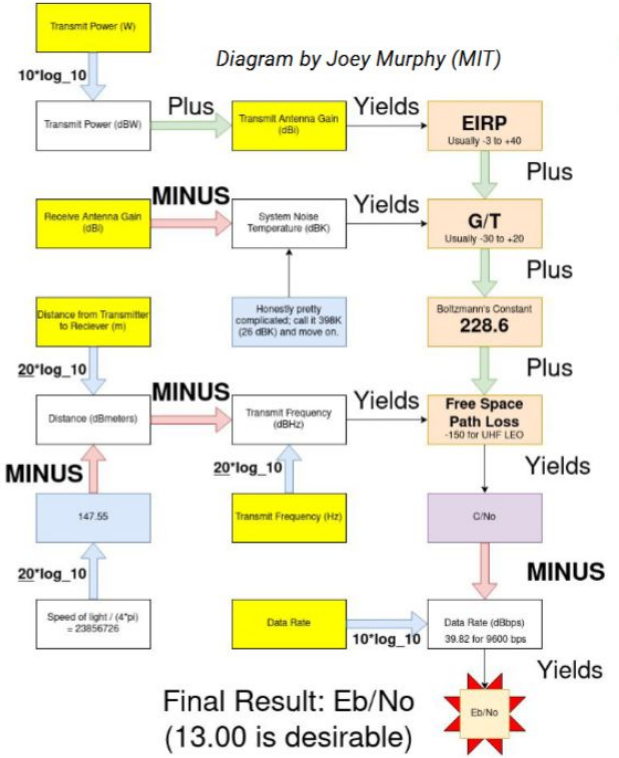
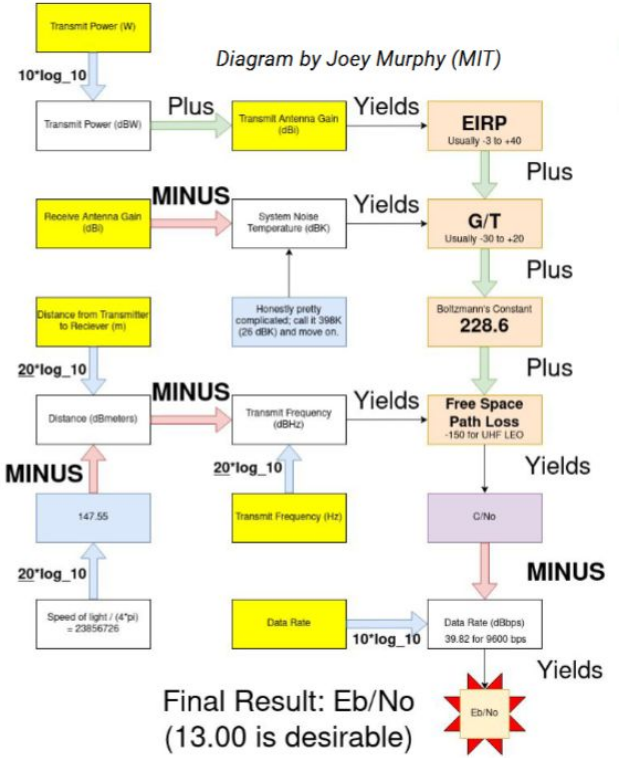
Calculations



RF vs Optical Trade Study: Downlink Bit Error and Data Rates				
	RF BER	RF Data Rate	Optical BER	Optical Data Rate
Orbiter-DSN	1.2E-23	22.67 kbps	2.94E-24	16.83 Mbps
Orbiter-Lander	9.82E-33	2.69 Mbps	–	–
Lander-DSN	9.61E-14	0.127 kbps	–	–

Calculations



RF vs Optical Trade Study: Uplink Bit Error and Data Rates				
	RF BER	RF Data Rate	Optical BER	Optical Data Rate
DSN-Orbiter	4.58E-33	3.2 Mbps	4.86E-26	18.2 Mbps
Lander-Orbiter	2.30E-28	270 kbps	–	–
DSN-Lander	1.53E-22	12.68 kbps	–	–

Full Link Budget- Orbiter-Lander

	Downlink (Orbiter -> Lander)		Uplink (Lander->Orbiter)	
	UHF Link	Laser Optic Link	UHF Link	Laser Optic Link
Parameters				
Distance (m)	8.00E+05		1.70E+06	
Transmit powers				
Ground transmit power (W)			7	
Ground transmit power (dBm)			8.4509804	
Satellite transmit power (W)	7			
Satellite transmit power (dBW)	8.4509804			
Transmit frequencies				
Ground transmit frequency (Hz)			430000000	
Ground transmit wavelength (m)			0.6971917628	
Ground transmit frequency (dBHz)			292.6693691	
Satellite transmit frequency (Hz)	430000000			
Satellite transmit wavelength (m)	0.6971917628			
Satellite transmit frequency (dBHz)	292.6693691			
Gains				
Ground antenna gain (dBi)	5		5	
Satellite antenna gain (dBi)	5		5	
Antenna gain-to-noise-temperature	**-22.48566995**		**-25.92430536**	

Full Link Budget - Orbiter - Lander

Losses		
Transmitted circuit loss (dB)		
Free space loss (dB)	-143.1789521	-149.7261308
Scintillation loss (dB)	-0.5	-0.5
Atmospheric and multi-path losses (dB)	-1	-1
Loss margin (%)	10.00%	10.00%
Total transmission loss (dB)	**-144.2650252**	**-150.8122039**
Environment		
Tranceiver Noise Figure (dB)	3.9	3.9
Reference Temperature (K)	210	210
System Noise Temperature (atm & frequency loss) (K)	255	504
Total System Noise Temperature (K)	560.4888723	1237.173294
Total System Noise Temperature (dBK)	27.48566995	30.92430536
Noise Power Density (W/Hz)	7.73E-21	1.71E-20

Full Link Budget - Orbiter - Lander

Outputs				
Effective isotropic radiated power, EIRP (dBm)	13.4509804	[redacted]	13.4509804	[redacted]
Carrier-to-Noise Ratio, C/N0 (dB)	75.30028523		65.31447113	
Received Power (dBW)	**-125.8140448**		**-132.3612235**	
Received Power (dBm)	**-95.81404482**		**-102.3612235**	
Target Data Rate (bps)	**100000**		**100000**	
Received Signal-to-Noise Ratio, Eb/N0 (dB)	**18.46964557**		**17.8043023**	

Full Link Budget- Orbiter-Earth

	Downlink (Orbiter->Earth)		Uplink (Earth->Orbiter)		n illumination efficiency
	X-Band Link	Laser Optic Link	X-Band Link	Laser Optic Link	0.5
Parameters					
Distance (m)	4.00E+11	4.00E+11	1.10E+11	400000000000	
Transmit powers					
Ground transmit power (W)			2000	5000	**Boltzman constant**
Ground transmit power (dBm)			33.01029996	66.98970004	1.38E-23
Satellite transmit power (W)	80	5			
Satellite transmit power (dBW)	19.03089987	36.98970004			**Speed of light**
Transmit frequencies					299792458
Ground transmit frequency (Hz)			8400000000		
Ground transmit wavelength (m)			0.03568957833	1.55E-06	DSN Receiver Gain (X-band 8420 Hz) [dBi]
Ground transmit frequency (dBHz)			318.4855857		68.41
Satellite transmit frequency (Hz)	8400000000				Sat Antenna Dia [m]
Satellite transmit wavelength (m)	0.03568957833	1.55E-06			2
Satellite transmit frequency (dBHz)	318.4855857				Effective Antenna Area
Gains					**1.570796327**
Ground antenna gain (dBi)	68.2		67.1		Sat Gain Check
Satellite antenna gain (dBi)	46.85		43.84		15496.9741
Antenna gain-to-noise-temperature (dB/K)	**44.73255945**		**20.79468488**		**41.90246907**

Full Link Budget - Orbiter - Earth

Losses					
Transmitted circuit loss (dB)					
Free space loss (dB)	-282.9745688		-271.7612226		
Scintillation loss (dB)	-0.1		-0.1		
Atmospheric and multi-path losses (dB)	-2		-2		
Loss margin (%)	10.00%		10.00%		
Total transmission loss (dB)	**-284.6606419**		**-273.4472958**		**-285.4884956**
Environment					
Tranceiver Noise Figure (dB)			2		
Reference Temperature (K)			290		
System Noise Temperature atm & frequency loss (K)	193		32		
System Noise Temperature RX (K)	29.2				
Total System Noise Temperature (K)	222.2	290	201.6190258	290	
System Noise Temperature (dBK)	23.46744055	24.62397998	23.04531512	24.62397998	
Noise Power Density (W/Hz)	3.07E-21	1.60E-23	2.78E-21	1.60E-23	**For APDs (4*kb*Tp)/RL where RL =1000 ohm**
Detector Bandwidth (Hz)		2.00E+06		2.00E+06	
NEP (Detector Sensitivity)		1.00E-19		1.00E-19	

Full Link Budget - Orbiter - Earth

Outputs				
Effective isotropic radiated power, EIRP (dBm)	65.88089987		100.1103	
Carrier-to-Noise Ratio, C/N0 (dB)	54.55281741		76.05768904	
Received Power (dBW)	**-150.579742**	**-145.83**	**-129.4969958**	**-144.814**
Received Power (dBm)	**-120.579742**	**-115.83**	**-99.49699584**	**-114.814**
Target Data Rate (bps)	**100000**	**100000**	**100000**	**100000**
Received Energy-to-Noise Spectral Density Ratio, Eb/N0 (dB)	**16.95078949**	**25.32970004**	**18.51618469**	**27.36170004**

Full Link Budget - Backup DSN

	Downlink (Lander -> Earth)		Uplink (Earth -> Lander)	
	X Band Link	Laser Optic Link	X Band Link	Laser Optic Link
Parameters				
Distance (m)	4.00E+11		4.00E+11	
Transmit powers				
Ground transmit power (W)			20000	
Ground transmit power (dBm)			43.01029996	
Satellite transmit power (W)	200			
Satellite transmit power (dBW)	23.01029996			
Transmit frequencies				
Ground transmit frequency (Hz)			8400000000	
Ground transmit wavelength (m)			0.03568957833	
Ground transmit frequency (dBHz)			318.4855857	
Satellite transmit frequency (Hz)	8400000000			
Satellite transmit wavelength (m)	0.03568957833			
Satellite transmit frequency (dBHz)	318.4855857			
Gains				
Ground antenna gain (dBi)	68.2		67.1	
Satellite antenna gain (dBi)	25		22	
Antenna gain-to-noise-temperature (dB/K)	**40.09095719**		**-2.017450822**	

Full Link Budget - Backup DSN

Losses		
Transmitted circuit loss (dB)		
Free space loss (dB)	-282.9745688	-282.9745688
Scintillation loss (dB)	-0.1	-0.1
Atmospheric and multi-path losses (dB)	-2	-2
Loss margin (%)	10.00%	10.00%
Total transmission loss (dB)	**-284.6606419**	**-284.6606419**
Environment		
Total System Noise Temperature (K)	647	252.2
System Noise Temperature (dBK)	28.10904281	24.01745082
Noise Power Density (W/Hz)	8.93E-21	3.48E-21
Outputs		
Effective isotropic radiated power, EIRP (dBm)	48.01029996	110.1103
Carrier-to-Noise Ratio, C/N0 (dB)	32.04061523	52.03220722
Received Power (dBW)	**-168.450342**	**-152.550342**
Received Power (dBm)	**-138.450342**	**-122.550342**
Target Data Rate (bps)	**100000**	**100000**
Received Signal-to-Noise Ratio, Eb/N0 (dB)	**14.32035988**	**16.72406526**

Comms Risk

		CONSEQUENCE				
		NEGLIGIBLE	MINOR	MODERATE	MAJOR	CATASTROPHIC
LIKELIHOOD	RARE				**RF interference (UWB- UHF- Xband)**	**Backup DSN link fails**
	UNLIKELY					**Failed antenna deployment**
	POSSIBLE				**Comms blackout from sun blockage**	
	LIKELY			**Antenna pointing**		
	ALMOST CERTAIN		**Radiation Damage**			