NAS Planetary Science and Astrobiology Decadal Survey Exploration Strategies for Venus

Radio Technologies

Potential Radios for Venus Missions

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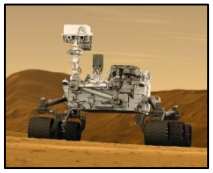
Outline

- JPL Software Defined Radios
- Radio Product Overview
- Electra UHF Transceiver
- Universal Space Transponder
- Mars Relay Network
  - Assets
  - Overview
  - Status
- Venus Telecom Subsystem Concept
- Challenges and Considerations

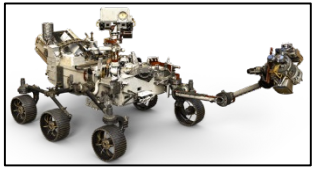
JPL Flight Software Defined Radio Developments



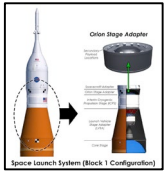
MSL Electra-Lite
UHF Relay Radio

CoNNeCT
S-band Radio

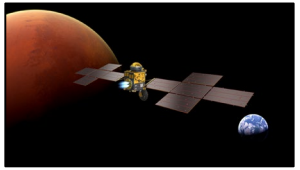
TGO Electra
UHF Relay Radio



M2020 Electra-Lite
UHF Relay Radio



Iris Transponders for
Artemis Secondary
Payloads

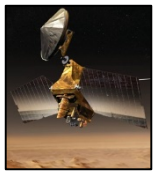


Mars Sample Return
Earth Return Orbiter

20+ YEARS OF ON-GOING DEVELOPMENT

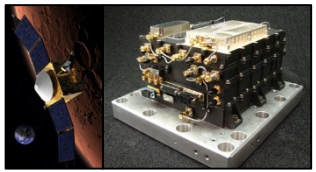
2005 … 2010 2012 2014 2016 2018 2020 2022 2024 2026 2028

MRO Electra
UHF Relay
Radio

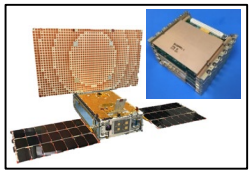


MSL Landing
Radar Digital
Assembly

MAVEN Electra
UHF Relay
Radio



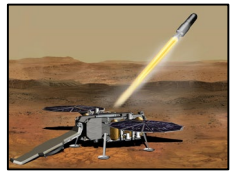
MarCO Iris Deep-
Space Transponder



M2020 Landing
Radar Digital
Assembly

NISAR Ka-band
Modulator

Mars Sample Return
Sample Retrieval Lander



Radio Product Overview

Electra

Electra UHF Transceiver (EUT)
UHF relay radio for orbiters/motherships

- At TRL-9 for earlier MRO, MAVEN, TGO versions
- New version in development for MSR using latest UST digital hardware and upgrades (FM target completion: 2023Q3)

E. Satorius, et al., "The Electra Radio" in Autonomous Software-Defined Radio Receivers for Deep Space Applications, Pasadena, Jet Propulsion Laboratory, 2006, ch. 2, pp. 19-43.

Electra-Lite UHF Transceiver (ELT)
UHF relay radio for landers/rovers/probes

- At TRL-9 for earlier MSL, M2020 versions
- UST-XU (below) likely to replace ELTs in future designs

L3Harris Technologies, "Mars Electra-Lite UHF Transceiver," 2021. [Online]. Available: https://www.l3harris.com/all-capabilities/mars-electra-lite-uhf-transceiver. [Accessed: 5-Jul-2021].

UST

UST – X-band/UHF (UST-XU)
Dual-band radio: UHF relay and X-band DTE/DFE

- New version in development for MSR using latest UST digital hardware, UST X-band design, and heritage ELT design
- FM target completion: 2024Q4

UST – Deep-Space (UST-DS)
Dual-band radio: S/X-band DTE/DFE

- Demonstrated TRL-6 with EM unit
- Used as the basis of all other UST variants

M. Pugh, et al., "The Universal Space Transponder: A next generation software defined radio," in *IEEE Aerospace Conf.*, Big Sky, MT, USA, 2017, Mar., doi: 10.1109/AERO.2017.7943866.

UST – Ka-band Modulator (UST-KaM)
High-rate Ka-band transmitter (25.5-27.0 GHz band)

- 2 Gbps OQPSK version delivered to NISAR (TRL-8)
- Higher rates (up to 4 Gsps) and higher modulation can be supported with firmware updates

M. Pugh, et al., "High-Rate Ka-Band Modulator for the NISAR Mission," in *IEEE Aerospace Conf.*, Big Sky, MT, USA, 2018, 3-10 March, doi: 10.1109/AERO.2018.8396451.

UST – Lite (UST-Lite)
Miniaturized relay/DTE/DFE radio (Quad band)

- In R&D, targeting TRL-5 by Sept. 2021
- Can support up to 4 RF bands simultaneously (eg: S/X/K/Ka)
- Miniaturized for SmallSat applications; configurable

Iris

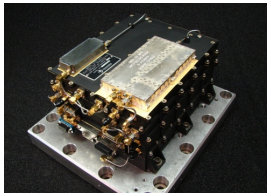
Iris Deep-Space Transponder
X-band DSN-compatible CubeSat Transponder

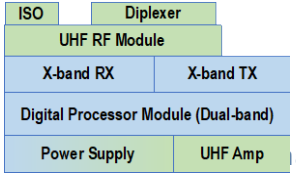
- At TRL-9 from MarCO, first interplanetary CubeSat to Mars
- Targeted for higher risk missions (e.g. tech demos, Class-D)
- Delivered to multiple Artemis secondary payloads

M. M. Kobayashi, et al, "The Iris Deep-Space Transponder for the SLS EM-1 Secondary Payloads," in IEEE Aerospace and Electronic Systems Magazine, vol. 34, no. 9, pp. 34-44, 1 Sept. 2019. doi: 10.1109/MAES.2019.2905923

Electra UHF Transceiver

Parameter	Electra UHF Transceiver (EUT)	Electra-Lite Transceiver (ELT)	UST-XU (UHF Relay portion)
Frequency Band (MHz)	390-405; 435-450	390-405; 435-450	390-405; 435-450
Data Rates	10 bps – 37.5 Mbps supported* 1 – 2048 kbps planned for MSR	1, 2, 4, 8, …, 4096 ksps	10 bps – 37.5 Mbps supported* 1– 2048 kbps planned for MSR
Modulation Schemes	Manchester, NRZ-L, BPSK, QPSK	Manchester, NRZ-L, BPSK, QPSK	Manchester, NRZ-L, BPSK, QPSK
Error Correction Coding	Conv (k=7, r=1/2), RS, LDPC	Conv (k=7, r=1/2), RS, LDPC	Conv (k=7, r=1/2), RS, LDPC
Receiver Noise Figure	FD: 4.9 dB; HD: 3.9 dB	FD: 4.0 dB (2 dB typ), HD: 3.9 dB (1.8 dB typ)	FD: 4.0 dB (2 dB typ), HD: 3.9 dB (1.8 dB typ)
Transmitter RF Power (min)	FD: 5.0 W; HD: 7.0 W	FD: 8.5 W; HD: 10.7 W	FD: 8.5 W; HD: 10.7 W
Protocols	CCSDS Prox-1, USLP†	CCSDS Prox-1, USLP†	CCSDS Prox-1, USLP†
Mass/Dimensions	5.3 kg; 21.7 x 24.5 x 11.6 cm	3.0 kg; 20.3 x 13.1 x 11.9 cm	6.0 kg; 20.0 x 24.5 x 13.0 cm (UHF+X)
DC Power (Rx, Tx/Rx incl'd PA)	23.9 W, 75.3 W	18.5 W, 65.0 W	20.6 W, 73.0 W
Total Ionizing Dose Radiation	50 krad*	20 krad	50 krad*
Processor/FPGA	66 MHz AT697F SPARC V8; Virtex XQR5V*	24 MHz TSC695F SPARC V7; Virtex XQ2V	66 MHz AT697F SPARC V8; Virtex XQR5V*
Command/Data Interface	MIL-STD-1553B/SpaceWire*	MIL-STD-1553B/LVDS	MIL-STD-1553B/LVDS
Additional Supported Features	Open-Loop Sampling (100 KSPS) Adaptive Data Rate (VCM) FDMA up to 2 channels*	Open-Loop Sampling (100 KSPS) Adaptive Data Rate (VCM)	Open-Loop Sampling (100 KSPS) Adaptive Data Rate (VCM)

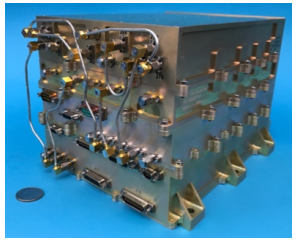


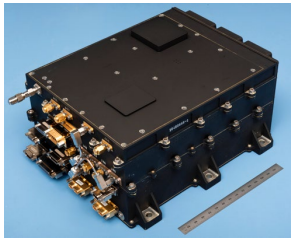


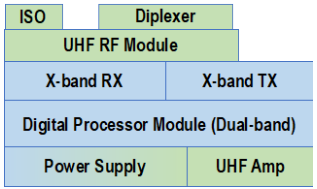
*New feature for MSR campaign
†Configurable with firmware/software updates

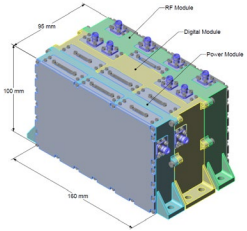
Universal Space Transponder

Parameter	UST Deep Space (UST-DS)	UST Ka-band Modulator (KaM)	UST-XU (X-band portion)	UST-Lite (in development)
Frequency Band	S (2.2-2.3 GHz); X (7.2/8.4 GHz)	25.5-27.0 GHz	X (7.2/8.4 GHz)	Up to 4 config. bands (eg: S/X/K/Ka)
Uplink Rates	7.8125 bps – 37.5 Mbps	N/A (transmit only)	7.8125 bps – 37.5 Mbps max	7.8125 bps – 1 Gbps max*
Downlink Rates	10 – 300 Mbps	0.5, 1.0, 2.0, 4.0 Gbps†	10 – 300 Mbps max	10 bps – 1 Gbps max*
Modulation Schemes	Manchester, NRZ-L, BPSK, QPSK	OQPSK, 8PSK†, 16APSK†	Manchester, NRZ-L, BPSK, QPSK	Manchester, NRZ-L, BPSK, QPSK
Error Correction Coding	Conv (k=7, r=1/2), RS, Turbo, LDPC	LDPC-7/8	Conv (k=7, r=1/2), RS, Turbo, LDPC	Conv (k=7, r=1/2), RS, Turbo, LDPC
Receiver Noise Figure	2.1 dB	N/A (transmit only)	2.5 dB	2.5 dB (typ for S/X band)
Receiver Sensitivity	-160 dBm @ 20 Hz LBW	N/A (transmit only)	-160 dBm @ 20 Hz LBW	-160 dBm @ 20 Hz LBW
Mass/Dimensions	5.4 kg; 20.0 x 24.5 x 15.9 cm	4.4 kg; 20.0 x 24.5 x 11.4 cm	6.0 kg; 20.0x24.5x13.0 cm (UHF+X)	1.5 kg; 16x10x10 cm (single band*)
DC Power	65 W (Tx/Rx dual band)	40.0 W (transmit only)	30.0 W (Tx/Rx single band)	20 W (single band*)
Processor/FPGA	AT697F SPARC V8; Virtex XQR5V	AT697F SPARC V8; Virtex XQR5V	AT697F SPARC V8; Virtex XQR5V	Leon-FT; Kintex XQRKU060
Command/Data Interface	MIL-STD-1553B/LVDS/SpaceWire	MIL-STD-1553B/SERDES	MIL-STD-1553B/LVDS	SpaceWire or RS-422/LVDS
Technology Readiness Level	TRL-6	TRL-8; TRL-9 by 2023	TRL-6; TRL-8 by 2024	TRL-5 by Sept. 2021





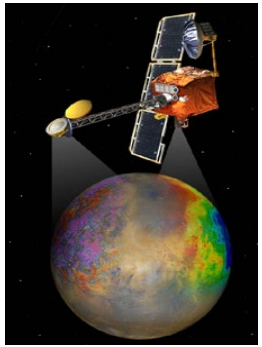




*Dependent on number of bands
†Configurable with firmware/software updates

Mars Relay Network Assets

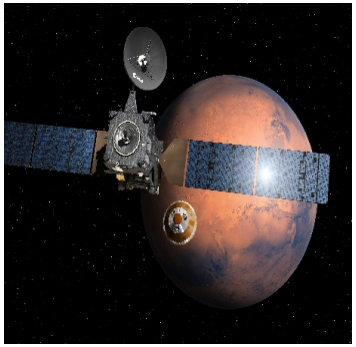
Orbiters



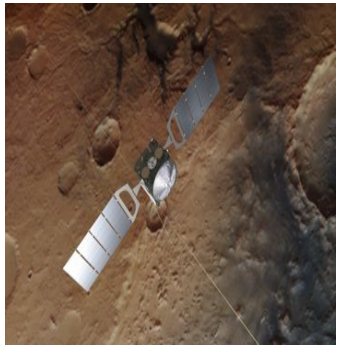
ODYSSEY

MRO

MAVEN



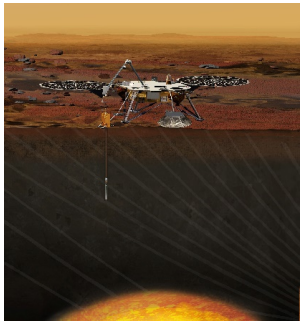
TGO



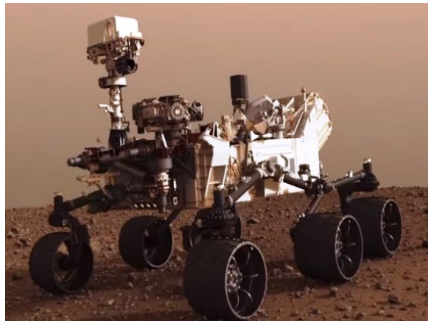
MEX

Landers

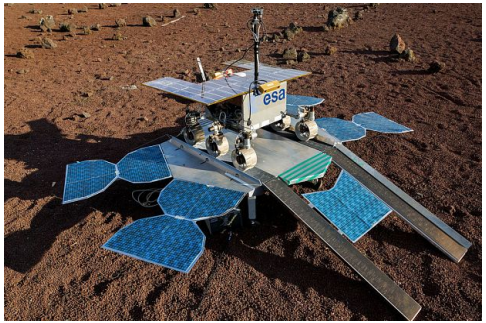
MSL



InSight

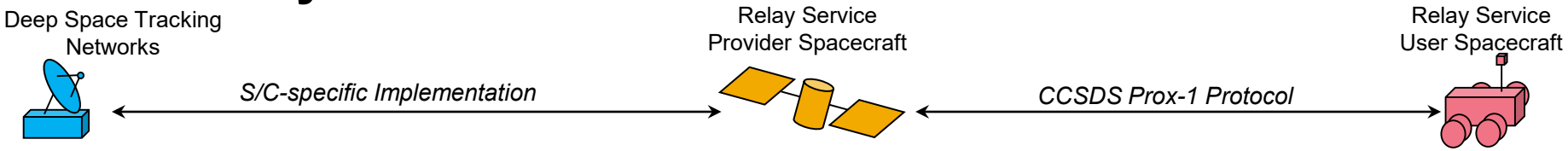


Mars 2020



ExoMars 2022

Mars Relay Network Overview



- NASA's DSN, ESA's ESTRACK
  - Reliable data transfer ensured by a variety of retransmission schemes (e.g. AOS retrans., ESA's PUS Service 13)
  - Pre-scheduled deep-space coverage
- Forward-link data products (Earth to Provider to User)
  - Data packaged as Provider Spacecraft data
  - De-packaged onboard for transfer to User
- Return-link data products (User to Provider to Earth)
  - Packaged on Provider Spacecraft as downlink
  - Directly transferred to User operators

- Reliable data transfer ensured by protocol
- Data rates up to 2 Mbps supported on Electra radios
- Adaptive Data Rate feature optimizes data rate based on link SNR performance
- Typically pre-scheduled relay activities, but emergency relay sessions also supported
- Relay services include:
  - Forward- and return-link data transfer
  - Full spectrum open-loop recording
  - Time correlation + clock setting
  - Radiometric tracking (2-way Doppler, Ranging)

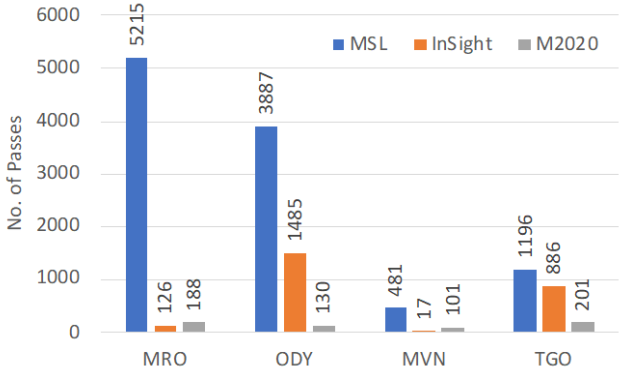
MaROS

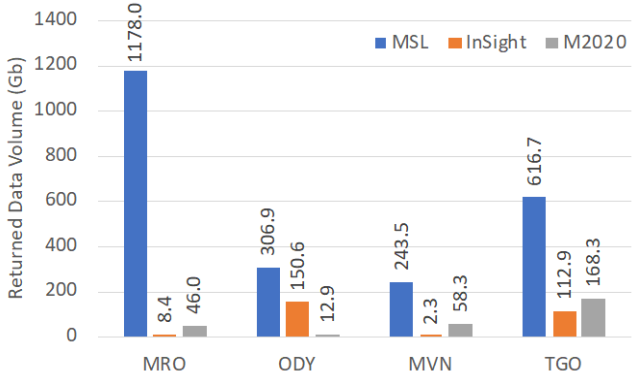
- Mars Relay Operations Service (MaROS)
  - Determines relay session opportunities from geometric view periods and mission-reported time limitations
  - Calculates data delivery times relative to relay sessions (i.e. latencies)
  - Identifies relay session planning and coordination conflicts.
  - Provides a single, standardized point-of-entry and repository for all relay planning and coordination data
  - Is entirely data driven and can be instantiated for any similar relay network.

Modified from the original chart courtesy of Roy Gladden and Mazen Shihabi

Mars Relay Operations Status

Orbiter	Orbit	Radio	ADR	Max Rate	LDPC	Notes
MRO	Sun sync	Electra	Yes	2 Mbps	Capable	Time-div split relay MSL/M2020 Consistent overflight & shift planning
ODY	Sun sync	CE-505	No	256 kbps	No	CE-505 is not re-programmable Consistent overflight & shift planning
MVN	Elliptical	Electra	Yes	2 Mbps	Equipped	Long overflight; shifts sol-to-sol LDPC upgrade: +3 dB link margin
TGO	Areocentric	Electra	Yes	2 Mbps	Planned	Long overflight; shifts sol-to-sol Time-div split relay MSL/M2020

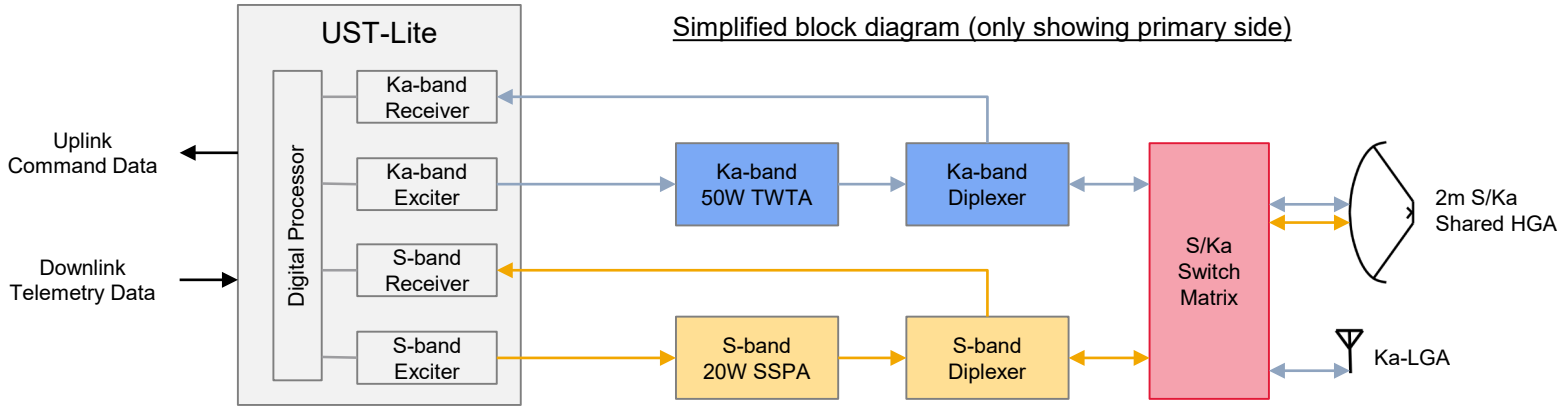




Total Returned DV:
MSL: 2.345 Tbits
InSight: 274.3 Gbits
M2020: 285.6 Gbits

Venus Telecom Subsystem Concept

- UST-Lite S/Ka dual-band configuration
- Ka-band DTE/DFE Comm
  - Venus-Earth distance: 1.7 AU max, 0.3 AU avg
  - Ka-HGA for nominal + Ka-LGAs for safe-mode
  - 50-100 watt TWTAs currently available from suppliers
- S-band Relay Comm
  - Orbiter avg altitude: ~35,000 km; During EDL, assume 120,000 km max slant range (example from a Venus balloon study)
  - Assume S-HGA on orbiter can be pointed to S-LGA on lander (simplifies comm if lander does not need to locate the orbiter)
  - 20 watt SSPA easily feasible today; higher power SSPAs using latest GaN devices possible



Venus Telecom Link Performance

Ka-band DTE/DFE	0.3 AU		1.7 AU		1.7 AU (Safe Mode)	
Link	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink
Supported Data Rate	**2 kbps**	**25 Mbps**	**2 kbps**	**750 kbps**	**125 bps**	**10 bps**
Link Margin	> 50 dB	3 dB	> 35 dB	3.3 dB	4.4 dB	5.6 dB
S/C Antenna	HGA		HGA		LGA	
S/C Ant Gain	54.5. dBi	54 dBi	54.5. dBi	54 dBi	8.7 dBi	9 dBi
DSN Antenna	34 m		34 m		34 m	
DSN EIRP or G/T	152 dBm	58.4 dB/K	152 dBm	58.4 dB/K	152 dBm	58.4 dB/K

Note: Uplink up to 2 kbps was investigated but higher rates could be supported with new DSN upgrades for LDPC encoded uplink

S-band Relay	35,000 km (Nom. Orbit)		120,000 km (EDL)	
Link	FWD to lander	RTN to Orbiter	FWD to lander	RTN to Orbiter
Supported Data Rate	**5 kbps**	**6 kbps**	**500 bps**	**500 bps**
Link Margin	10 dB	10 dB	10 dB	10 dB
S/C Antenna	HGA		HGA	
S/C Ant Gain	30.7 dBi	30.3 dBi	30.7 dBi	30.3 dBi
Lander Ant Gain	4 dBi	5 dBi	4 dBi	5 dBi

- MRO orbit is 250-316 km, compared to much higher orbits at Venus
- EDL typically at 8 kbps, but longer slant range for Venus reduces data rate capability
- Nominal orbit also shows lower data rates compared to Mars relay

Challenges and Considerations

- Lander-Orbiter range is critical in $1/r^2$ power-distance relationship
- Venus lander electronics likely will need to be cooled
  - Antennas could be designed for high-temperature operation
  - SSPAs are typically 30-40% efficient at S-band; high thermal dissipator, especially if higher transmit power is desired
- Using an LGA on the lander side will simplify the telecom design so that the lander does not need to locate the orbiter in the sky
- Electra Radio has been the work horse for Mars relay, but currently only supports UHF. S-band version would need to be developed, but the more agile UST platform may be the ideal solution to merge DTE/DFE and relay comm into one radio package (similar to UST-XU for MSR)
- Similar relay service to the Mars Relay Operations Service (MaROS) can be developed for orbiters at Venus to support future landed assets, balloons, and probes

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