Small Aerostationary Telecommunications Orbiter Concepts for Mars in the 2020s

Robert E. Lock, Charles D. Edwards Jr., Austin Nicholas, Ryan Woolley, David J. Bell,
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr
Pasadena, CA 91109
818-393-2525
Robert.E.Lock@jpl.nasa.gov

Abstract—**Current Mars science orbiters carry UHF proximity payloads to provide limited access and data services to landers and rovers on Mars surface. In the era of human spaceflight to Mars, very high rate and reliable relay services will be needed to serve a large number of supporting vehicles, habitats, and orbiters, as well as astronaut EVAs. These will likely be provided by a robust network of orbiting assets in very high orbits, such as areostationary orbits. In the decade leading to that era, telecommunications orbits can be operated at areostationary orbit that can support a significant population of robotic precursor missions and build the network capabilities needed for the human spaceflight era. Telecommunications orbiters of modest size and cost, delivered by Solar Electric Propulsion to areostationary orbit, can provide continuous access at very high data rates to users on the surface and in Mars orbit.**

TABLE OF CONTENTS

1. INTRODUCTION

Current Mars science orbiters carry UHF proximity payloads to provide limited access and data services to landers and rovers on Mars surface. These use omnidirectional antennas with twice-daily access for ~10 minutes per contact opportunity, and provide data rates from 100s of kb/s to as much as 2 Mb/s. While data rates to Earth can be 1-5 Mb/s (20-200 Gb/sol), only about 0.5 Gb/sol of that can be returned, per landed asset, by such limited relay opportunities.

In the era of human spaceflight to Mars very high rate and reliable relay services will be needed to serve a large number of supporting vehicles, habitats, and orbiters, as well as astronaut EVAs. These will likely be provided by a robust network of orbiting assets in very high orbits, such as areostationary orbits. Figure 1 shows an example of the types of elements and connecting links that might be needed.

In the decade leading to that era, telecommunications orbiters can be operated at areostationary orbit that can support a significant population of robotic precursor missions and build the network capabilities needed for the human spaceflight era. These orbiters would demonstrate the capabilities and services needed for the future but without the high bandwidth and high reliability requirements needed for human spaceflight.

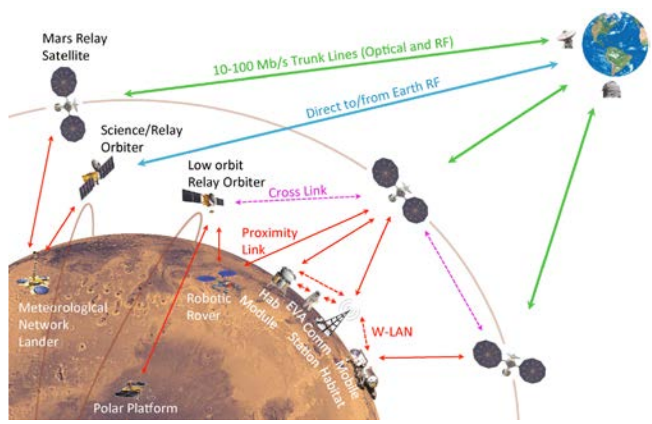

Figure 1. A possible future Mars telecommunications network for the era of human spaceflight to Mars.

Telecommunications orbiters of modest size and cost, delivered by Solar Electric Propulsion to areostationary orbit, can provide continuous access at very high data rates to users on the surface and in Mars orbit. We will show two examples highlighting the wide variety of orbiter delivery and configuration options that could provide high-performance service to users. The first is a small, very low-cost orbiter concept that could be delivered by a SEP science orbiter spiraling through the areostationary orbit altitude on the way to low Mars orbit. At about 200 kg, this orbiter would support 50 kg of RF and optical telecommunications payloads. Capability and performance would be sufficient to demonstrate the preponderance of services and support functions needed in the human mission era but would be well suited to robotic precursor missions. A second orbiter example departs from a geosynchronous transfer orbit at Earth, where it might have been co-manifested with another orbiter. This orbiter, weighing about 1000 kg, employs Solar Electric Propulsion (SEP) to transfer to Mars and establish itself in areostationary orbit. The large payload mass and power available would allow a very high performance direct-to-Earth (DTE) data rate pipeline and extremely high-rate relay capabilities in RF and optical links. This capable payload, comprised of about 140 kg of RF and optical elements, would demonstrate all desired services for future orbiters and could support an order of magnitude more users than the current low Mars orbit relay network can provide.

Descriptions of the example orbiters will include configuration views, mass, power and delta-V budgets, cost analogies, and detailed telecommunications payload mass and performance lists. Example mission timelines, trajectories, and operations concepts will be presented.

2. MARS RELAY NETWORK ARCHITECTURE

Currently, three National Aeronautics and Space Administration (NASA) orbiters and one European Space Agency (ESA) orbiter operate at Mars with capability to provide relay telecommunication services to users on the Martian surface. As shown in Figure 2, NASA's orbiters include the 2001 Mars Odyssey spacecraft, the Mars Reconnaissance Orbiter (MRO), and the Mars Atmosphere and Volatile Evolution Mission (MAVEN). Odyssey and MRO currently provide operational relay support to the Opportunity and Curiosity rovers on the surface of Mars, while MAVEN has demonstrated its relay functional capability and is slated for use once its primary science mission is complete. In addition, ESA's Mars Express Orbiter, launched in 2003, continues to serve as an additional backup relay asset, and has been used to support tracking of the Phoenix Lander and Mars Science Laboratory spacecraft during their entry, descent, and landing on Mars. ESA's ExoMars/Trace Gas Orbiter (TGO), with a planned launch in 2016, carries a NASA-provided relay payload. In addition to conducting its own primary science mission it is expected to provide relay services to NASA and ESA landers.

This Mars relay network infrastructure has been built up by the economical approach of adding relay payloads to orbiters intended to conduct science from low Mars orbits. This approach comes with some important compromises in terms of relay access opportunities and performance.

For most science orbiters the orbit is typically selected based on the science mission objectives mainly driven by high resolution observation requirements. This translates into low-altitude, high inclination, circular orbits, with orbit altitudes of ~300-400 km. The low altitude results in low slant ranges, enabling high data rates even with low gain UHF antennas at both ends of the link, but very short contact durations. However, the high inclination orbit results intermittent contacts, usually 2 to 3 times per day, to a given user on the Martian surface.

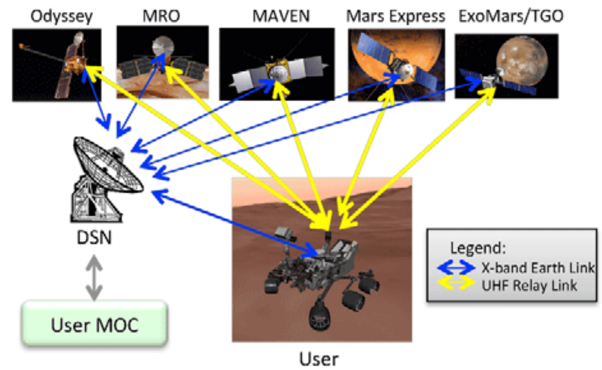

Figure 2. Current and Near-term Mars Telecom Relay Network Link Diagram.

All of these science orbiters carry UHF relay transceivers. MRO, MAVEN, and TGO each deploy versions of NASA's Electra UHF Transceiver offering data rates up to 2048 kbps, while Odyssey and Mars Express carry older transceiver designs with lower data rate capabilities. Each orbiter incorporates a downward-looking, low-gain UHF antenna, with surface users incorporating a fixed upward looking low-gain UHF antenna, enabling simple relay operations.

Not all science orbiters are located in similar or coordinated orbits. The result of this is short intermittent contacts with long gaps, that are distributed unevenly and variably during a given Sol of rover operations. The intermittent nature of these relay contact opportunities has a significant impact on the operations paradigm for landed missions.

Given the intermittent contacts and short contact durations, even with relatively high data rates, the data return capability of each orbiter for a Curiosity-class lander ranges from 100 to 300 Mb/sol [2].

3. RELAY FROM MARS AREOSTATIONARY ORBIT

There are many high altitude orbits that are useful for relay to surface and orbiting missions, many of which are shown in [5]. High altitude orbits all have much longer access times than low altitude orbits and have other useful properties depending on the mission. Areostationary orbits and areosynchronous orbits have an orbit period equal to a Mars sol and remain continuous visible to users for which they have been positioned. Figure 3 shows geometric footprints for areostationary and areosynchronous orbiters at Mars.

An areostationary orbit at Mars stays fixed over a specific longitude and over the equator ($i = 0°$). Its altitude is 17032 km above the surface and slant ranges to landed elements on the surface are less than 20,000 km for elevation angles above 10 degrees. Orbiter mission users in lower Mars orbits, for example within the orbit of Phobos, have slant ranges less than 30,000 km.

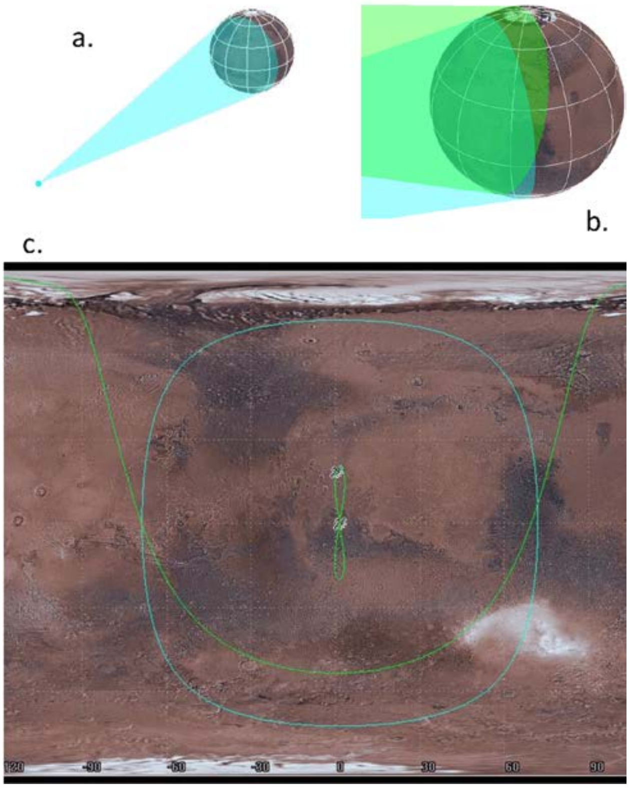

Figure 3. Accessibility footprint views for Mars surface users (10° elevation) with Areostationary orbiter (blue) and Areosynchronous orbiter (green) at 21° inclination. a) View of areostationary access on Mars globe. b) Close up view of areostationary and areosynchrous shown superimposed. c) both footprints on a Mars Cartesian Map. The figure-eight indicates the groundtrack of the areosynchronous orbit over the course of a single Sol.

Areosynchronous orbits have the same altitude, orbit period and eccentricity (e = 0°) but inclination can be varied to allow the orbiter to be visible in the extreme North and South latitudes. Landed elements in the low and mid latitudes would still have continuous views of the orbiter above 10° elevation but the orbiter would appear to move in the sky in a figure-eight pattern. While slightly more complex for antenna pointing, a wider range of missions could be supported from a single orbiter.

Areosynchronous or areostationary orbits would be selected based on other network orbiter capabilities, expected user locations and bandwidth needs. For example, a Mars Phoenix-like polar lander might not have access to an areostationary orbiter but would have access to a high inclination science or other relay orbiter which could choose to cross-link data to the areostationary relay orbiter or directly to Earth. On the other hand, a polar landed element would have access for many hours per sol to an areostationary orbiter. A Mars relay network could be comprised of an areostationary orbiter and optionally a low Mars orbiters (such as a science orbiter), or an areosynchronous. Either of these choices would extend the networks reach to polar regions and to other longitudes but also add redundancy and robustness by providing alternate paths for data and commanding.

Delta-V (ΔV) requirements for maintaining longitude position for areostationary orbits are shown in figure 4. Orbiters described in this paper assumed they would be provisioned for 10 years of stationkeeping and attitude control operations regardless of expected orbiter lifetimes. The ΔV is tangential to the orbit and orbit maintenance might be needed once or twice per month in the mission.

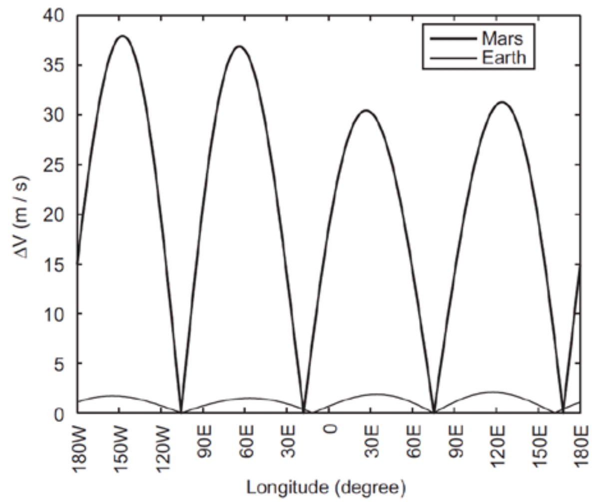

Figure 4. Annual ΔV requirements from Mars areostationary longitudes. Earth values are included for comparison. Any Mars surface mission can be served from one of the four low-ΔV longitudes [4].

This paper will use the areostationary orbit as reference for analysis and description. The orbiter concepts described below would be very similar for most high altitude orbits.

4. TELECOM ORBITER OPTIONS

A wide variety of orbiter types and high altitude orbits could be used productively to construct a useful relay network at Mars. In the context of building to a representative architecture to support the era of human exploration, the initial orbiters are expected to establish useful and demonstrative subsets of the architecture. These subsets are programmatically selectable based on available budget, delivery opportunities, and consideration of users needs in the mission timeframe. For example, a future science orbiter intended for low Mars orbit could be provided with very high capacity RF and optical communications links for direct-to-Earth and proximity relay functions. This would result in advancing a subset of the goals for the eventual architecture but keep the short and infrequent access times available in current orbiters. In another example, a very small orbiter with moderate capability links sent to an areostationary orbit would provide not only long and frequent access opportunities users but permit broad access to a wide variety of missions beyond landers and rovers.

Many past and current NASA and commercial missions have already demonstrated the functions and capabilities needed for initial orbiters in a future relay network. The NASA Explorers Program SMEX missions provide examples of low cost, low mass missions intended to provide high value science investigations. The spacecraft designed for these missions use industry standard components and development methods, are relatively small (100-300 kg) and low cost (<$120M, including launch). Some commercial telecommunications spacecraft are low cost and posses many of the attributes needed for Mars. Factors unique to Mars and other planetary missions make it unlikely that these orbiter designs could be used directly but the components and development methods are applicable. Past Mars missions such as Odyssey and Mars Global Surveyor are good examples of modest size and cost spacecraft that would make excellent platforms for telecom orbiters at Mars.

Telecommunications payloads for areostationary relay orbiters would have many flight proven designs but also would have new components designed to provide the advanced capabilities needed in the coming decades. For the most part telecom system components are industry standard procurements, although some amplifiers would need additional qualification for new environments or power levels. The main exceptions would be the radios and optical systems. Software defined multiple frequency transponders will be fully qualified in the near future. These would be needed to both manage multiple links and link types for Mars relay and for DTE communications and to provide functional and flexible redundancy in the face of hardware faults. Optical systems have been used for years in near Earth environments out to Lunar ranges. Deep space optical communications are ready for demonstration in planetary missions. Proximity optical communications systems are new, however, and require development and demonstration. Including them in the initial missions could provide a very high rate and low mass and power infrastructure for future missions to make use of.

Telecom elements used in the Mars telecom/relay orbiters presented here include:

- Multi-frequency, software defined transponders
- 0.5, 1.0, and 2.0 meter high gain antennas (HGA) for use at X-band and Ka-band
- Medium gain antennas (MGA) for use at X-band and UHF
- Simple switch networks to cross-strap multiple transponders and antennas
- 20 W, 100 W and 200 W TWTAs
- Multi-channel gimbals to articulate Mars facing antennas
- A deep space optical communication terminal
- Proximity optical communications terminals (include independent gimbals for telescope pointing)

Configurations of these elements might include single string with simple functionally and redundant switching of separate elements for small low cost orbiters up to fully redundant, multiply switched components for high reliability, long life orbiters.

A convenient configuration and attitude plan adopted for this paper would be spacecraft with body-fixed Earth-pointed antennas and optical communications terminals, combined with directional links continuously pointed at Mars. Gimbals or other rotating devices would need to survive for less than 4000 cycles for a 10-year mission.

Data rates for the systems will depend on orbiter size and resources available (budget, mass and power). Smaller spacecraft will be mass, power and volume limited and will therefore have lower DTE data rates but might still have significant relay data rates due to the relatively small HGAs needed for the relatively short range to Mars. Limited resources would also lead to reduced component redundancy and flexibility.

As larger budgets allow spacecraft to be made larger, more capability can be accommodated and more user services can be offered. This can take the form of larger apertures, higher power amplifiers (and larger solar arrays to drive them), more frequency selections and types of antennas, larger switch networks for flexibility and resiliency, high reliability components (heavier or redundant components). This forms a continuum of orbiter sizes and payload capability.

In the era of human spaceflight to Mars, telecom orbiters would very likely be required to offer many services and be highly reliable and resilient. In the next decade, the highest priority services and capabilities could be demonstrated for the robotic science and human exploration precursor missions by smaller, moderate cost orbiters. The implementation and deployment of these orbiters would reduce design uncertainty, provide installed operations infrastructure, and enable demonstrations of improved hardware and software technologies, operational practices and services.

Of the many orbiters that could provide an evolutionary step to future capabilities, this paper presents two low cost options for initial capability that provides experience in key future capabilities but also supports existing and near future missions in Mars orbit and on the surface. The first is a small orbiter, similar to Small Explorer (SMEX) mission orbiters, that could be carried to Mars and dropped-off in its working orbit. The second type is a moderate sized orbiter that could share a launch to Geosynchronous Transfer Orbit (GTO) at Earth and then transfer to Mars orbit using SEP.

5. Small Drop-off Telecom Orbiter

This orbiter type would be carried to Mars by a Solar Electric Propulsion (SEP) powered mothership bound for low Mars orbit. The small orbiter would be dropped off in aerostationary orbit near its desired longitude. The small orbiter would then deploy its solar arrays and antennas and begin providing relay services for 5-10 years. An example science orbiter shown with a volume envelope to carry a small telecom orbiter can be seen in Figure 5.

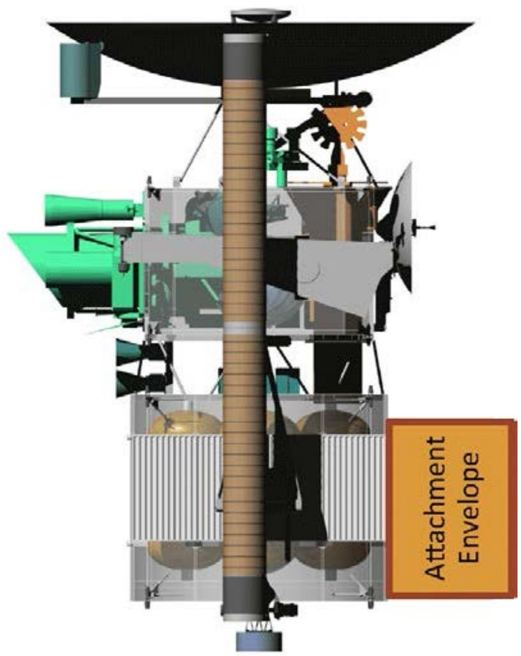

Figure 5. Example Mars science orbiter with volume shown to support an option to carry a small telecom orbiter daughter-craft.

The baseline concept presented here would have a spacecraft with a body fixed DTE link and a Mars pointed articulated proximity link. The spacecraft would be light (150-200 kg) and low cost (following the SMEX model.) It would have a nominal 5 year life, single string design but with some functional redundancy in the telecom payload configuration.

The telecom payload would have a DTE with a 1m HGA and a 100 W TWTA at Ka-band. The uplink would be at X-band, matching the standard DSN configuration. A lower power 20 W TWTA would provide a backup X-band downlink for bad weather and spacecraft safing events. The proximity relay links would include an articulated platform with a 0.5 m HGA supporting two-way x-band communications, Ka-band receive, and a small optical terminal. Two transponders would be included to provide simultaneous operation of the DTE and proximity links. A simple switch network would allow switching antennas for user requested links (X or Ka-band) to the transponder and would also provide cross-strapping of the transponders and X-band TWTAs for limited redundancy. Failures in those systems would only partially degrade the orbiters functionality by limiting the simultaneous DTE and proximity functions rather than eliminating the entire end-to-end system. The RF components are estimated to weigh 43 kg (with contingency) and require 320 W for continuous operations. The optical components would weigh less than 6 kg and require 43 W to operate continuously. This orbiter concept would not be large enough to accommodate the mass or volume of a deep space optical terminal in addition to the DTE RF systems.

After considering the payload mass, articulation, and power needs, a parametric spacecraft modeling tool was used to estimate the spacecraft subsystems, including margin. The tool is based on previously flown spacecraft in a similar size range. Model inputs included, payload mass, articulation type, pointing accuracy, payload power, range to Sun, and ΔV budget. Table 1 shows resulting key orbiter sizing parameters including orbiter mass, power budget, solar array size and BOL power, battery capacity, ΔV and propellant budgets.

Table 1. Mass, Power, and ΔV values for baseline orbiter concept.

MEL, kg		194
Bus	139	
Telecom Payload	50	
Propellant	5.4	
ΔV, m/s		64
Main	0	
RCS	64	
Power		
Bus Power Budget, kW	0.46	
Battery Capacity, Ahr	24	
Solar Array, kW@ 1AU	1.2	

The resulting orbiter concept configuration would be just under 1m on each side. This should accommodate 6 one-meter solar array segments with room to grow to 10 segments, a 1 m offset feed high gain antenna for DTE communications, a 50 cm high gain antenna for proximity relay communications at X and Ka-bands.with a gimbal to rotate 360 deg/sol, a high accuracy attitude control system, and a high speed command and data handling system to handle autonomous scheduling, network routing, and tracking of user assets with high data volume throughput. Figure 6 shows the orbiter concept in its fully deployed configurations and in its stowed configuration.

Blah blah add more talk about orbiter concept so that the page breaks in a nice place and the figures and tables line up just friggen right. Because writing a paper isn't bad enough without MS Word adding so much finicky time to the process. OMFG, this is pointless.

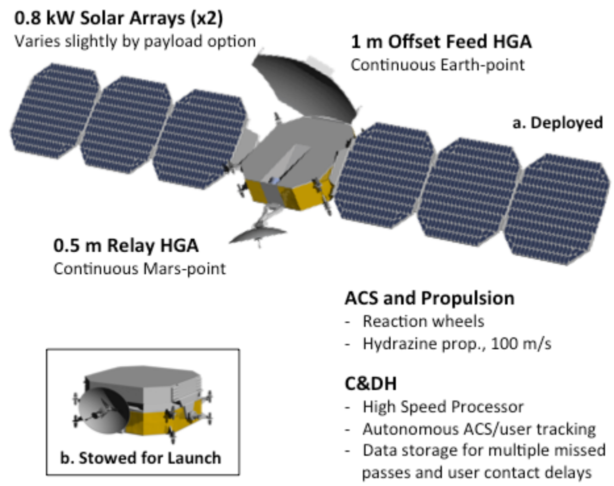

Figure 6. Example layout for a small telecom orbiter daughtercraft. a) Deployed view after separation from mothership and deployments. Key features such as solar arrays, antennas are labeled. Key internal functionality is described. b) stowed configuration prior to launch.

To test the sensitivity of the orbiter design concept, two variations on the telecom payload were created, each with different mass and power requirements. The first was a minimum payload which deleted the optical proximity terminal mass and power. The second payload variation was a more robust payload with additional antennas, frequency bands and component redundancy. This increased the mass significantly since it was mainly hardware. Power increases were more modest being entirely from optical proximity telecom improvements. Table 2 shows the comparative model results of the orbiter with the payload variants.

Table 2. Mass, Power, and ΔV values for baseline orbiter concept and payload variants.

	B/L P/L	Min P/L	Robust P/L
MEL, kg	194	180	220
Bus	139	132	152
Telecom Payload	50	43	62
Propellant	5.4	5.0	6.2
ΔV, m/s	64	64	64
Main	0	0	0
RCS	64	64	64
Power			
Bus Power Budget, kW	0.5	0.42	0.52
Battery Capacity, Ahr	24	21	27
Solar Array, kW@ 1AU	1.2	1.1	1.4

Additionally a parametric sweep of payload mass and power was created to show the overall sensitivity of design and model. Figure 7 shows a plot of the sensitivity of total spacecraft mass as payload mass and power requirements change. Data points for orbiter concepts with the payload variants are highlighted. This plot can be used to estimate orbiter mass for any desired payload mass and power in the telecom payload tradespace.

The system performance of the baseline telecom payload is expected to be significantly greater than the entire Mars Odyssey mission and the MRO relay mission. This is mainly due to balanced design of DTE and relay throughput for dedicated telecom access and lack of competition with science payloads. Details of performance links is shown in section 7.

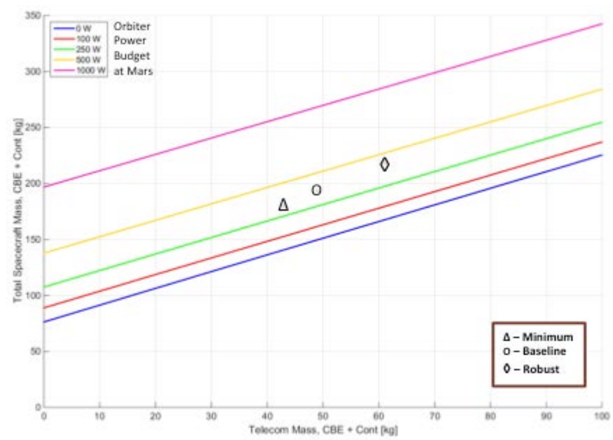

Figure 7. A plot of total spacecraft mass vs telecom payload mass of the orbiter concept design. The lines represent total orbiter power demand, reflecting the power demands for payload variations.

Although this concept is low redundancy, being largely single string, the lifetimes should be able to reach beyond five years as exemplified by several SMEX missions (e.g. GALEX) and the Mars Exploration Rovers, Spirit (7 years) and Opportunity (12 years and counting). This should be possible through parts screening and system testing.

6. Co-Manifest Launch Telecom Orbiter

This orbiter concept would employ solar electric propulsion (SEP) to transfer from an Earth Geosynchronous transfer orbit (GTO) to a Mars areostationary orbit. Its low mass design would be able to share a launch with many commercial or government spacecraft bound for geosynchronous orbits.

A relevant example of two spacecraft sharing a ride to GTO is the 2015 launch of two stacked Boeing 702SP spacecraft to GTO on a single Falcon-9 launch vehicle. Each spacecraft then used SEP to transfer to its own separate GEO orbit [11]. The Falcon-9 delivers approximately 4400 kg to GTO. Depending on the launch adapters used to enable a co-manifest and the mass of the other spacecraft, there might be 1500-2000 kg available for the Mars telecom orbiter

In this case any GTO orbit or rideshare partner would be sufficient as the Mars telecom orbiter would use SEP to spiral out from GTO to an escape trajectory. As shown in Figure 8, from there the orbiter would transfer to Mars and then spiral down to a Mars areostationary orbit.

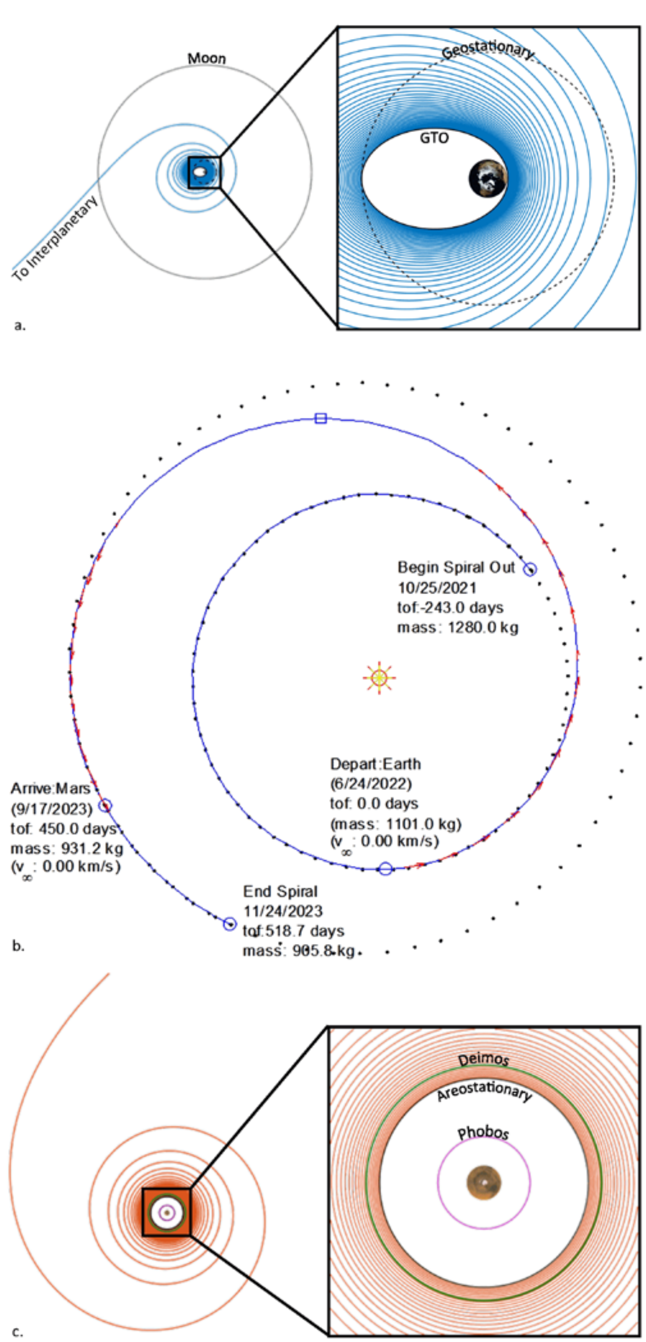

Figure 8. a. Example SEP trajectory departing from Earth GTO for a Mars telecom orbiter on a co-manifest launch. Inset shows an expanded view of the trajectory spirals inside GEO orbits. b. Example SEP trajectory from Earth to Mars. Example SEP trajectory arriving at Mars. Inset shows an expanded view of the trajectory spirals near areostationary orbits.

These trajectories require 2 years to reach Earth escape, 1.4 years to reach Mars, and 0.8 years to reach aerostationary orbit. The SEP system would use 250 kg of Xenon propellant to make the trip. The stationkeeping ΔV requirements for any longitude as shown in figure 4, would be achievable by 10-20 kg Xenon.

The baseline concept presented here would have a spacecraft with a body fixed DTE link and a Mars pointed articulated proximity link. The spacecraft would be of moderate mass and cost and comparable to existing geocomm designs. It would have a nominal 10 year life, dual string design with additional functional redundancy in the telecom payload configuration.

The telecom payload would have a DTE with a 2m HGA and a 200 W TWTA at Ka-band. A Deep Space Optical Communications (DSOC) terminal would also be included in the payload. The RF uplink would be at X-band, matching the standard DSN configuration. An optical uplink signal would come from the Table Mountain Observatory as a command source and optical beacon. A lower power 20 W TWTA would provide a backup X-band downlink for bad weather and spacecraft safing events. The proximity relay links would include an articulated platform with a 1 m HGA supporting two-way X-band, Ka-band receive, an X-band medium gain antenna (MGA) two-way UHF with an MGA for critical event coverage, and a small optical terminal. Three transponders would be included to provide simultaneous operation of the RF DTE and proximity links. A switch network would allow switching antennas for user requested links (X or Ka-band) to the transponder and would also provide cross-strapping of the transponders and X-band TWTAs for redundancy. The RF components would weigh 93 kg (with contingency and including gimbals) and would require 650 W for continuous operations. The optical components would weigh 46 kg and require 120 W to operate continuously.

After considering the payload mass, articulation, and power needs, a parametric spacecraft modeling tool was used to estimate the spacecraft subsystems, including margin. The tool is based on previously flown spacecraft in a similar size range (Odyssey, DAWN, MAVEN, MRO). Model inputs included: payload mass, articulation type, pointing accuracy, payload power, range to Sun, and ΔV budget. Table 3 shows resulting key orbiter sizing parameters including orbiter mass, power budget, solar array size and BOL power, battery capacity, ΔV and propellant budgets.

The resulting orbiter concept configuration would be of similar size to earlier Mars missions and Discovery missions such as Odyssey, MGS, and DAWN, and would fit in a similar payload volume. This should accommodate stowed solar arrays and fixed dish antennas. Deployable antennas are possible and would increase telecom performance with an increase in development cost and mission risk.

Table 3. Mass, Power, and ΔV values for baseline orbiter concept.

MEL, kg		1122
Orbiter Bus	678	
Telecom Payload	139	
Propellant	306	
Delta V, m/s		8874
Main	8790	
RCS	84	
Power		
Bus Power Budget, kW	0.86	
Battery Capacity, Ahr	43	
Solar Array, kW@ 1AU	12	

Figure 9 shows the orbiter concept in its fully deployed configurations and in its stowed configuration. A ROSA array is shown for convenience, however Ultraflex and flat panel arrays would very likely be accommodated. The stowed configuration is representative of a lower berth launch adaptor and its volume constraints. A berth above another orbiter in the co-manifest would allow a less restrictive stowed configuration.

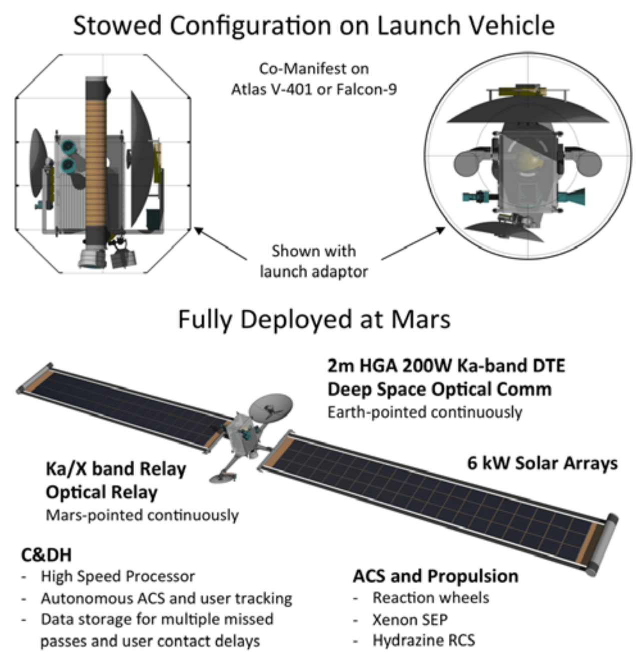

Figure 9. Example layout for a Co-manifest Launch telecom orbiter. Stowed view in launch vehicle and Deployed view after separation.

7. System Performance Estimates

Both orbiters share much of their design and components, however, they each have different antennas and power amplifiers and optical comm configurations. This means they each have significantly different link performance. This section shows data rates and volumes for each system.

Drop-off Small Telecom Orbiter – Link performance

The system performance of the baseline telecom payload was estimated as shown in Figure 10. The 100 ka-band TWTA and 1m HGA provide DTE 200 kb/s to over 3 Mb/s. These data rates are many times the equivalent rates from the Mars Odyssey spacecraft which has been a mainstay of Mars network relay operations for the past 13 years.

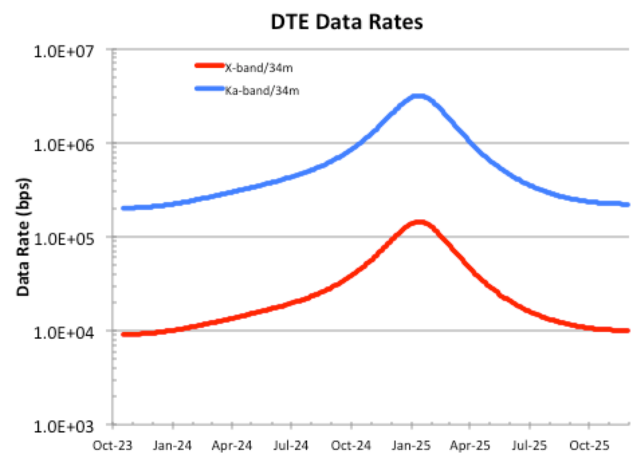

Figure 10. Link performance at X-band and Ka-band to DSN 34m stations.

Depending on user loading timing and frequency the telecom orbiter might use continuous DSN coverage (in parallel with other missions using multiple spacecraft per aperture) or might require fewer passes per day. Figure 11 show the data volume available per DSN pass at Ka-band and X-band. For continuous coverage this could be 3 times better.

The small orbiter carries a 50 cm Proximity HGA for use with X and Ka-band. Figure 12 shows the data rate performance for the small orbiter for various Lander antenna sizes and 10 W. Scaling with lander power is linear.

Optical proximity performance is shown in Table 5. The small orbiter carries a 5 cm telescope. For lander telescopes of 5 or 10 cm and 1 or 2 W, the data rates vary from 5 to 50 Mb/s. This shows comparable performance to the Ka-band system but with much lower mass, power and volume.

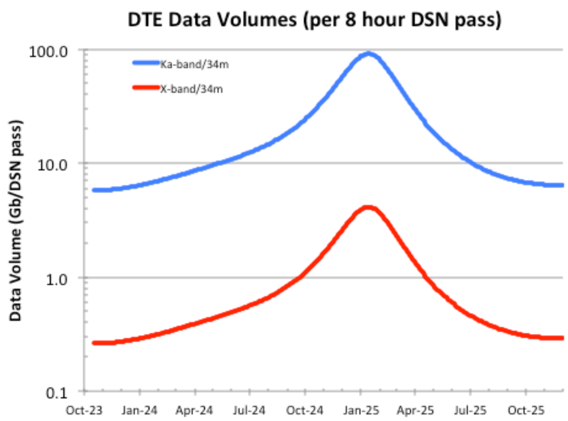

Figure 11. DTE data volumes to DSN 34m antennas at X-band and Ka-band. Assumes 8 hour pass and no occultations by Mars.

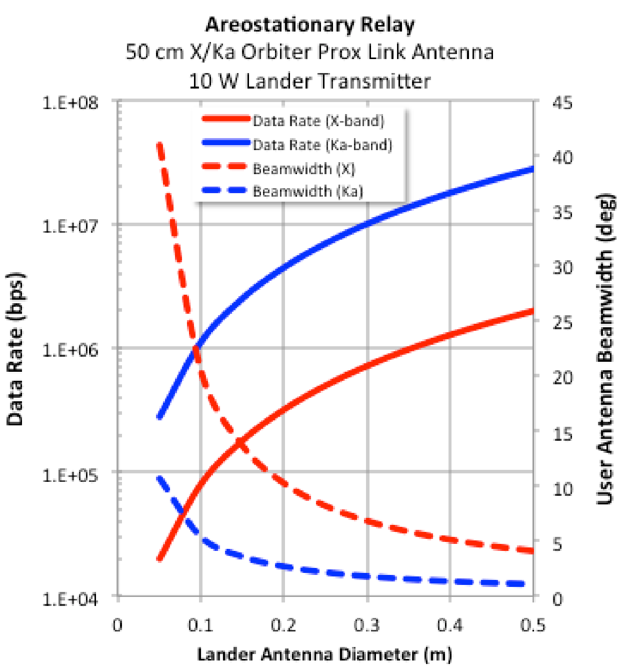

Figure 12. Proximity relay link performance at X-band and Ka-band for a range of lander antenna sizes, all with 10 W transmitter power and to a 50 cm telecom orbiter antenna.

Table 5. Proximity Optical data rates to arestationary orbit for an orbiter telecope with 5 and 10 cm optics and a surface asset telescope with 5 cm optics and 1 or 2 W laser power.

		Areostationary Orbiter Tx 980 nm	5 cm dia. (Mb/s)	10 cm dia. (Mb/s)
Surface Asset Tx 808 nm	5 cm dia.	1W	5	20
		2W	15	50

Co-manifest Launch Telecom Orbiter – Link performance

The system performance of the baseline telecom payload was estimated as shown in Figure 13. The 200 Ka-band TWTA and 2m HGA provide DTE from 1 to 20 Mb/s. These data rates are many times the equivalent rates from the MRO spacecraft which has been the major contributor of Mars network relay data return for many years. The orbiter would also carry a DSOC terminal which would provide significantly higher data rates.

Data volumes from this orbiter would support an order of magnitude more surface and orbital assets and more than an order of magnitude more daily data volume than previous Mars relay capability.

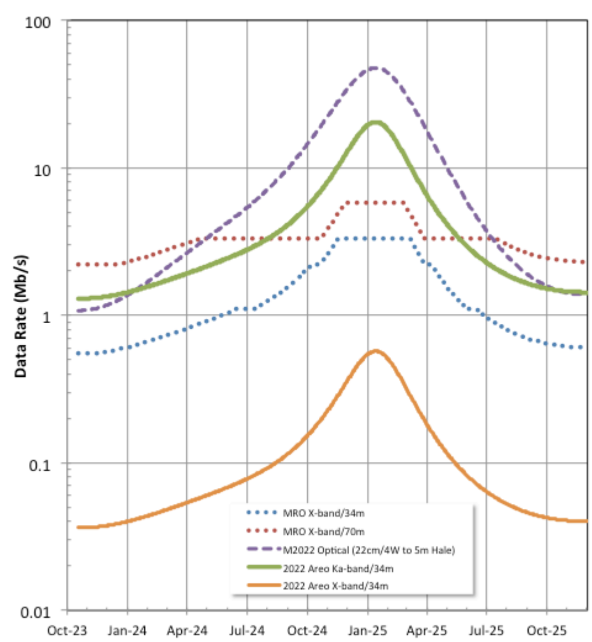

Figure 13. DTE link performance at Optical to 5m Hale Telescope, and X-band and Ka-band to 34m DSN stations. Comparisons to MRO X-band to 34m and 70m DSN Stations are included for reference.

Proximity data rates are shown in figure 15. Because of the large directional antenna, data rates are considerable and would very likely limited to receiver capabilities on-board the orbiter. This would still be 10s of Mb/s, an order of magnitude more that current UHF orbiter links and for much longer durations.

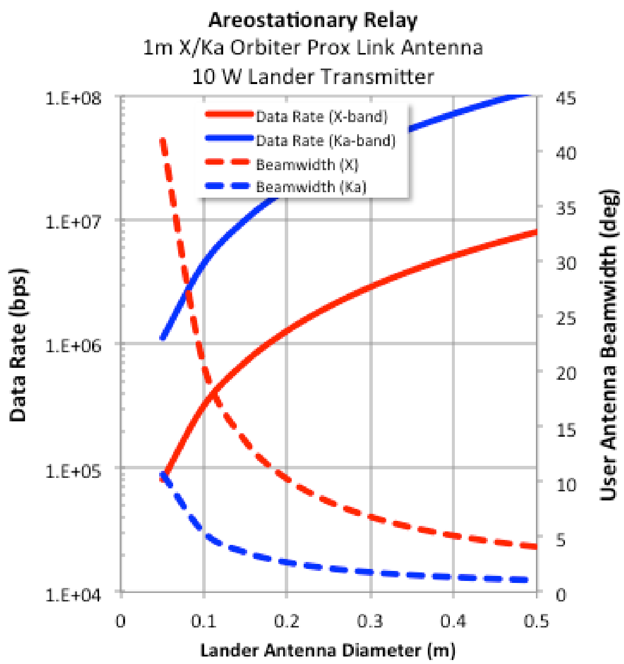

Figure 14. Proximity relay link performance at X-band and Ka-band for a range of lander antenna sizes, all with 10 W transmitter power and to a 1m telecom orbiter antenna.

8. CONCLUSION

In the era of human spaceflight to Mars very high rate and reliable relay services will be needed to serve a large number of supporting vehicles, habitats, and orbiters, as well as astronaut EVAs. These could be provided by a robust network of orbiting assets in very high orbits. In the decade leading to that era, telecommunications orbiters could be operated at areostationary orbit that could support a significant population of robotic precursor missions and build the network capabilities needed for the human spaceflight era. These orbiters could demonstrate the capabilities and services needed for the future but without the high bandwidth and high reliability requirements needed for human spaceflight.

Telecommunications orbiters of modest size and cost, delivered by Solar Electric Propulsion to areostationary orbit, could provide continuous access at very high data rates to users on the surface and in Mars orbit. Two examples highlighting the wide variety of orbiter delivery and configuration options were shown that could provide high-performance service to users.

The first was a small, very low-cost orbiter concept that could be delivered by a SEP science orbiter spiraling through the areostationary orbit altitude on the way to low Mars orbit. At about 200 kg, this orbiter would support 50 kg of RF and optical telecommunications payloads. It could demonstrate the preponderance of services and support functions needed in the human mission era but would be well suited to robotic precursor missions, providing about an order of magnitude higher relay rates and data volumes than current orbiters can provide.

A second orbiter example was shown that would depart from a geosynchronous transfer orbit at Earth, where it might have been co-manifested with another orbiter. This orbiter would employ Solar Electric Propulsion (SEP) to transfer to Mars and establish itself in areostationary orbit. The large payload mass and power available would allow a very high performance direct-to-Earth (DTE) data rate pipeline and extremely high-rate relay capabilities in RF and optical links. This capable payload, comprised of about 140 kg of RF and optical elements, would demonstrate all desired services for future orbiters and could support an order of magnitude more users than the current low Mars orbit relay network can provide.

Orbiters like these could provide telecom relay benefits over and above the current capabilities at Mars and extend service to a wider variety of missions for science, exploration precursor needs and prove out the techniques needed in the human spaceflight era.

ACKNOWLEDGEMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] C. D. Edwards, "Relay Communications for Mars Exploration," *Int. J. Satell. Commun. Network*, **25** 111-145, 2007.

[2] C. D. Edwards, Jr., et al., "Proximity Link Design and Performance Options for a Mars Areostationary Relay Satellite." *Aerospace Conference, 2016 IEEE*. IEEE, 2016.

[3] C.D. Edwards, J.T. Adams, D.J. Bell, R. Cesarone, R. DePaula, J.F. Durning, T.A. Ely, R.Y. Leung, C.A. McGraw, S.N. Rosell, "Strategies for telecommunications and navigation in support of mars exploration" *Acta Astronautica*, 48 (2007), pp. 661–668.

[4] Silva, J., Romero, P., "Optimal longitudes determination for the station keeping of areostationary satellites." *Planetary and Space Science* 87 (2013): 14-18.

[5] Noreen, G., Kerridge, S., Diehl, R., Neelon, J., Ely, T., Turner, A., "Mars orbits with daily repeating ground traces," in *13th AAS/AIAA Space Flight Mechanics Meeting*, Ponce, Puerto Rico, 2003.

[6] Z.J. Bailey, T.D. Kowalkowski, R.E. Lock, E.J Sturm, and R.C. Woolley, "Round-Trip Solar Electric Propulsion Missions for Mars Sample Return," *24th AAS/AIAA Space Flight Mechanics Meeting*, AAS Paper 14-365, Santa Fe, NM, Feb. 2014.

[7] T.D. Kowalkowski, Z.J. Bailey, R.E. Lock, E.J Sturm, and R.C. Woolley, "Robotic Mars Exploration Trajectories Using Hall Thrusters," *24th AAS/AIAA Space Flight Mechanics Meeting*, AAS Paper 14-364, Santa Fe, NM, Feb. 2014.

[8] Lock, R., Bailey, Z., Kowalkowski, T., "Mars Sample Return Orbiter Concepts for the Post-Mars2020 Decade," Jet Propulsion Laboratory, California Institute of Technology, *2014 IEEE Aerospace Conference*, Mar. 1-8, 2014.

[9] C. D. Edwards, Jr., et al., "Replenishing the Mars relay network." *Aerospace Conference, 2014 IEEE*. IEEE, 2014.

[10] R.C. Woolley and A.K. Nicholas, "SEP Mission Design Space for Mars Orbiters," *AIAA/AAS Astrodynamics Specialist Conference*, AAS Paper 15-632, Vail, CO, Aug. 2015.

[11] https://spaceflightnow.com/tag/boeing-702sp/

BIOGRAPHY

Rob Lock *received his B.S. degree in Mechanical Engineering from Cal Poly, San Luis Obispo in 1985. He has been with JPL for more than 25 years. He currently leads orbiter mission formulation studies for the Mars Exploration Program Office at JPL. He has been Mission Manager for the JPL payloads on the ExoMars Trace Gas Orbiter mission, lead mission planner for Mars Reconnaissance Orbiter mission and mission planning team chief for the Magellan Mission to Venus. He was the lead systems engineer for the Jupiter Europa Orbiter mission study and has led systems engineering, operations design, and aerobraking design for Mars Scout proposals. His career started with work on ISS, Strategic Defense Initiative, and Magellan spacecraft development at Martin Marietta Aerospace in Denver Colorado.*

Charles (Chad) Edwards, Jr. *is the Chief Telecommunications Engineer for the Mars Exploration Program and Chief Technologist for the Mars Exploration Directorate at the Jet Propulsion Laboratory. Prior to this current assignment he managed the research and development program for NASA's Deep Space Network. He received an A.B. in Physics from Princeton University and a Ph. D. in Physics from the California Institute of Technology.*

Austin K. Nicholas *received a B.S. degree in Aerospace Engineering from University of Illinois at Urbana-Champaign in 2011. He received an S.M. in Aeronautics and Astronautics from the Massachusetts Institute of Technology in 2013. He currently works for JPL in the Project Systems Engineering & Formulation Section. His primary focus is developing concepts for various Mars missions, including Mars Sample Return. At MIT, he worked on attitude and cluster control for a formation-flight Cubesat mission using electrospray propulsion and architecture exploration for low-cost human missions to the lunar surface.*

Ryan Woolley *received a B.S. in Physics-Astronomy from Brigham Young University in 2003, a M.S. in Astronautical Engineering from USC in 2005, and a Ph.D. in Aerospace Engineering from the University of Colorado in 2010. He has been with JPL since 2005. Ryan began his tenure as a systems engineer in the Mars Mission Concepts group and has since transferred to the Inner Planets Mission Design group. He has worked on nearly all aspects of the Mars Sample Return campaign and has developed various tools to evaluate mission designs and architectures. He is currently working on the Next Mars Orbiter specializing in low-thrust mission design.*

David J. Bell *is the supervisor of the Communications Systems & Operations group, 337H at the Jet Propulsion laboratory and has over 30 years experience in all aspects of flight and ground radio system design including modulation, coding, antennas, propagation and interference mitigation. Mr. Bell has published numerous telecom technical papers and holds several patents related to antennas and coding systems for telecom operations in difficult propagation and signal environments. Mr. Bell was the system engineer for the development, flight build and test of the first Electra Software defined radio subsystem that enables relay telecom service on the MRO, MSL, MAVEN Mars spacecraft.*

APPENDIX A

Summary of Format Requirements

Paper size
8.5 x 11 inch

Number of pages
6–20

Margins
Top and bottom: 0.75 inch
Left and right: 0.75 inch

Columns
Number of columns: 2
Space between: 0.25 inch

Font
Times Roman 10 pt regular, unless otherwise noted

Text
Line spacing: Single
Space after paragraph: 10 pt
Paragraph indent: None
Justification: Left & right

Title
20 pt bold, upper & lower case
Initial caps on all words except articles, conjunctions and prepositions
Centered on the full-page width
Maximum length 100 characters

Author(s)
10 pt bold, upper and lower case
Centered on the full-page width
Name, affiliation, postal address, phone number, and e-mail
No degrees or titles, except military rank

Abstract
9 pt bold

Acronyms
Define acronyms on first usage

Page numbers
Bottom center of each page, including first page

Footnotes
8 pt regular

Unnumbered Footnote for Copyright notice on Page 1:
978-1-4673-7676-1/16/$31.00 ©2016 IEEE

Government or Crown employees use text below:
U.S. Government work not protected by U.S. copyright
978-1-4673-7676-1/16/$31.00 ©2016 Crown

For assistance, see FAQ link to the right

Headings
Spacing before major or subheadings: Double space
Spacing after major or subheadings: 1.5 space
Major headings: 12 pt small caps, bold, centered
Subheadings: 10 pt italic, flush left, separate line
Subsubheadings: 10 pt italic, run into paragraph with em dash
No headers. Footers used only for page numbers and Copyright notice on page 1.

Equations
Centered in column
Equation numbers in parentheses, flush right
Include special fonts with the paper.

Figures and Tables
Captions and titles: 10 pt bold
Figure captions: Centered directly below figures
Table titles: Centered directly above tables
Scanned images: 300 dpi JPEG

References
List references at end of paper.
References numbers: In square brackets [ ]

Biography
Brief biography in 10 pt italic and photo of each author, use bold italic for each author name.

Submission to the website
Use 2013 Authors Instructions as Word template.
Convert Word to PDF.
Carefully check for format conformance.
Embed all fonts used.
Remove passwords from paper.
Scan for viruses.
Submit **only properly formatted PDF** copies to the website both for review and final paper.

FAQ on formatting issues see:
Format FAQ

Access to the IEEE PDF eXpress site for conversion to, and/or validation of, PDF manuscripts see:
IEEE PDF eXpress

IEEE copyright form
Filled-out, signed IEEE copyright form must be submitted by the Final Paper Deadline. Submission is via the **eCF** link on the website on the same page (but not the same link) used to submit papers.

For submission of copyright forms in original paper forms by mail, see the instructions on the Author's Instructions page on the website.