High-Capacity Communications from Martian Distances Part 2: Spacecraft Antennas and Power Systems

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1. Abstract

This paper summarizes recent advances in antenna and power systems technology to enable a high data rate Ka-band Mars-to-Earth telecommunications system. Promising antenna technologies are lightweight, deployable space qualified structures at least 12-m in diameter (potentially up to 25-m). These technologies include deployable mesh reflectors, inflatable reflectarray and folded thermo-setting composite. Advances in 1kW-class RF power amplifiers include both TWTA and SSPA technologies.

2. Introduction

Recent advances in antenna and power systems technology show great potential to enable a high data rate Ka-band Mars-to-Earth telecommunications system [1]. The spacecraft payload power vs. antenna diameter trade space is quite large with antenna diameter options spanning 6–25 meters and RF power varying from hundreds to thousands of watts. Several deployable antenna technologies show promise for a lightweight 12 to 25-m class space qualified structure that meets accommodation and stowage requirements. These technologies include deployable mesh reflectors, inflatable reflectarray and folded thermo-setting composite. This paper presents a brief overview of the key electrical and physical performance characteristics for the most promising technologies. In addition, the relative advantages of the various technical approaches are compared.

Power amplifiers are another key enabling technology for high data rate communications. Link budget calculations indicate that 1kW-class RF power amplifiers are required. This paper presents a brief overview of current state of the art and future developments in both TWTA and SSPA technologies aimed at meeting this goal.

3. State of the Art in Antenna Technology

Several technologies can be used to realize a 6- to 25-m class deployable antenna. These include reflector antennas, phased arrays, reflectarrays and discrete element lenses. The principle of operation for the first three is illustrated in Figure 1. Mesh reflector antennas are currently the predominant technology used in commercial and military telecommunications applications. Because of launch vehicle shroud size limitations, deployable antennas are essential for apertures exceeding approximately 4.5 m. Current deployment mechanisms utilize folded composites. Inflatable technology shows promise, but is not yet sufficiently mature. The discussion below summarizes the current state-of-the-art and suggests potential for each technology to achieve a low mass, low cost, space qualified Ka-band antenna technology.

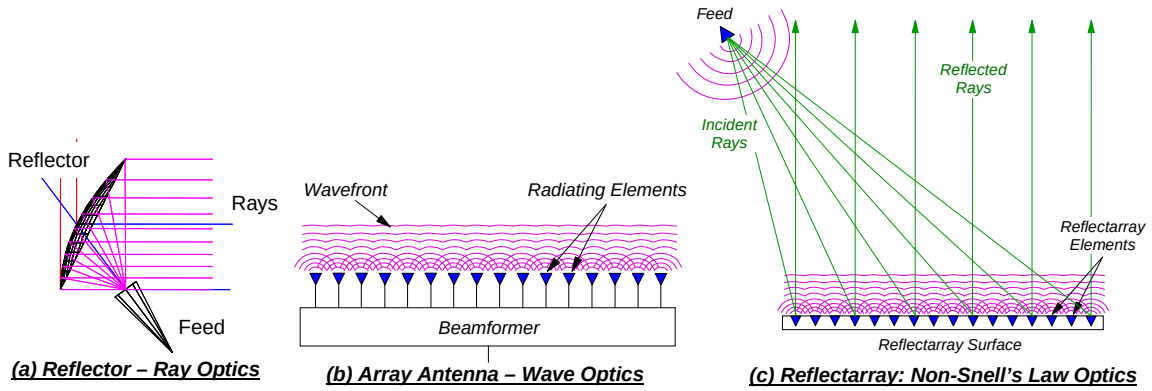

Figure 1: Basic principles of (a) Reflector, (b) Phased Array and (c) Reflectarray antennas

Deployable mesh reflectors are widely used for commercial telecommunications applications in Earth orbit due to their low mass density (typically 1-2 kg/m^2 with deployment booms) and compact stowed volume [2,3].The key limitations of mesh reflectors at Ka-band are mesh reflectivity and surface accuracy. Commercial telecomm applications typically use L-band and S-band, where surface accuracy and reflectivity are not challenging. The current state-of-the-art is roughly Ku-band, and there are indications that a limit exists at about Ka-band above which mesh reflectors may not be practical. The stowed size of mesh reflectors is limited by folding the support structure. Deployment reliability is generally good, although there have been notable failures such as Galileo.

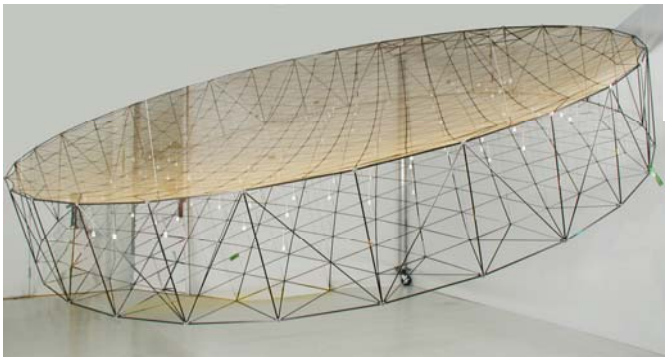

Figure 2 AstroMesh Deployable Mesh Reflector (courtesy NGST)

Solid (non-deployable) composite reflectors have relatively low mass density (~3-4 kg/m^2), very high surface accuracy, excellent reflectivity and high efficiency. Although the size of a solid composite reflector is limited by the launch vehicle fairing diameter, the construction technique is of interest because it is used in solid element deployable antennas (discussed below) and deployment structures. In the typical composite structure, graphite epoxy face sheets are bonded to a nomex or aluminum honeycomb core. When high reflectivity is needed, the composite structure is coated with a metallic reflecting surface such as vapor-deposited aluminum (VDA). The inherent rugged construction and low coefficient of thermal expansion makes these reflectors ideal for harsh space environments. Flight units up to 3-m diameter at Ka-band have achieved TRL 9.

Solid element deployable reflector antennas extend the size of composite reflectors by folding multiple composite surfaces. Such antennas are an excellent design solution for spaceborne applications that require larger aperture sizes operating at frequencies above approximately 30 GHz. The deployable aspect of this design allows for apertures exceeding 4.5 m, and the solid element aspect—with its greater surface precision—allows for RF operations at frequencies well above 30 GHz. The solid elements themselves are usually lightweight composite structures (e.g. graphite-epoxy skins with aluminum-honeycomb core). The element shape can vary, ranging from simple folding edges (as in the ETS-VI antenna) to more complex, nested polygonal shapes (as in the TRW Sunflower) [3].

Various folding techniques have been demonstrated in laboratory experiments and show promise for obtaining the reflectivity and surface accuracy needed for very high frequency reflectors—94 GHz reflectors have been demonstrated. It is very likely this technology can achieve TRL 6 at Ka-band with good efficiency. However, the composite molding process is usually expensive, and the addition of a relatively complex mechanism to deploy the folded surfaces accurately into position means this is likely to be a comparatively high cost option.

Inflatable antenna technology is the most recent development in deployable reflectors. Inflatable structures potentially represent a very attractive design solution for spaceborne antennas that require large apertures operating in the low- to mid-frequency regime, and several design concepts show promise for Ka-band. The Echo balloon—one of the earliest satellites of the space age—was an inflatable antenna structure, and interest in this class of structures has increased since the in-space demonstration of the Inflatable Antenna Experiment (IAE) in 1996. Inflatable structures are important because of their potential to enable a new class of lightweight large aperture structures requiring very high packaging efficiency with variable stowed geometry. Indeed, a key advantage of inflatable technology is the potential to deploy a boom mechanism that supports the feed or subreflector as an integral part of the reflector structure.

The inflatable structure paradigm hinges on employing materials that are flexible and easily packaged for launch, and capable of being inflation-deployed and rigidized in space. The key issues with inflatable antenna technology are surface accuracy and reliability. At present, the rigidization mechanisms are not yet considered to be at a sufficient TRL for flight demonstration. In addition to purely inflatable antennas, there are several examples of hybrid technologies that combine inflatable with conventional antennas and deployment structures. These hybrid antenna structures seek to mitigate risk factors associated with inflatable antennas.

Reflectarray is a relatively new technology that holds the potential for enabling inexpensive flat-surface reflector antennas, such as a flat membrane inflatable. This concept reduces the requirement for generating a doubly curved reflecting surface and the need to employ a rigidization mechanism over the entire reflector surface. Reflectarray antennas are inherently narrowband (typical percentage bandwidth in the range of 3-5%), but their bandwidth easily meets a 500-MHz bandwidth requirement at Ka-band. However, it is difficult to design a high efficiency reflectarray that covers multiple frequency bands that are not harmonically related.

The TRL of a reflectarray antenna is dependent upon the reflectarray substrate material and the deployment mechanism. To date, no reflectarray has flown in space, although a recent design achieved at least TRL 5 in flight qualification testing for an Earth Science project [4]. That design uses flat panels unfolded with a standard mechanical deployment mechanism constructed of composite material and reflectarray panels constructed using standard printed circuit technology. Reflectarray technology of that type has the potential for very high stowage density because the panels “stack” and can easily reach TRL 6 by 2010 because the design uses standard technology. The folding geometry is adapted to narrow aspect ratio “z-fold” structures, so a practical mechanical folding design is needed to make this technology useful for greater than 6-m class circular antennas.

A flat membrane reflectarray (FMR) holds the promise of much lower mass density than a folded flat panel reflectarray (e.g. see [5] and [6]). A FMR is somewhat analogous to a tensegrity mesh reflector antenna in that the reflector surface is stretched over a frame structure. However, a mesh reflector approximates an ideal doubly-curved reflector surface (e.g. a parabola) whereas an FMR surface is flat and uses the special reflectarray surface to focus the beam. Mass density is very low because there is no need for a structural support for the panels; stowage efficiency is typical of what one expects for inflatable antennas. Development models of the FMR use an inflatable support frame, although a folded mechanical frame is possible. FMR inflatable technology is currently at about TRL 4 and can reach TRL 6 by 2009 for a 10-m class antenna.

Figure 3 Inflatable Flat Membrane Reflectarray Antenna

Active Phased Array Antennas using both mechanically folded (z-fold) and inflatable truss structures are currently in development for space based radar applications (e.g. 3 x 300 m at X-band). Active array technology has been used for commercial telecommunications applications such as the Iridium satellite telephone system. Active arrays offer advantages in terms of long-term robust operations due to the "graceful degradation" property; loss of a few elements does not result in a catastrophic failure of the system. However, because these antennas have a significantly higher mass density (> 5 kg/m^2) and are very expensive compared to reflector technology, active arrays are not competitive for large aperture telecommunications applications.

Discrete element lens is a thin, planar device which employs an array of printed circuit radiators (e.g. patch antenna) on both outer surfaces. Corresponding patches on the two sides of the lens are connected to each other with a variable length strip transmission line. The lengths of the striplines are adjusted to collimate the beam from a feed at the lens focal point. Lens antennas have the advantage of being quite robust because the transmission phase is very insensitive to surface positional tolerance. For this reason, lenses may have potential for a stretched membrane concept. However, the multiple layers needed to achieve a modulo 360º phase results in a significantly higher mass density than a corresponding stretched membrane reflectarray. Two notable lens experiments that have been reported place this technology at approximately TRL 3 for Ka-band.

4. Transmitter Power Requirements

The transmitter technology challenge is to achieve RF powers in the range 100-1000 kW at relatively low mass and volume. Table 1 provides a mass and volume summary for TWT-based (traveling wave tube) and solid-state power amplifiers (SSPA) power requirements in the range of hundreds of watts, with a kilowatt and beyond being achieved by power combining.

Table 1: Power amplifier performance estimates versus output power.

Power (Watts) & Device Type	Eff %	Device		EPC		PA Mass (kg)	PA Mass Dens. (kg/W)	PA Vol (cm3)	PA Vol Dens (cm3/W)	Solar Array Mass (kg)	Radiator Mass (kg) (67 W/kg)	Total Mass (kg)	Power Dens (kg/W)
		Mass (kg)	Vol. (cm)	Mass (kg)	Vol. (cm3)								
100 (Helical Ka-Band TWT)	60	2.5	30x10x10	1.5	15x15x10	4	.024	5250	31.5	1.8	1	6.8	.068
100 (Helical Ka-Band TWT)	55	2.5	30x10x10	1.5	15x15x10	4	.012	5250	16	3.6	2.2	9.8	.054
250(Helical Ka-Band TWT)	50-55	3.0	35x10x10	2.5	15x15x10	5.5	.012	5250	15.1	5.0	3.1	13.6	.054

1000 (By Combining four 250 Watt TWTs)	45-50	3.0x4 + 1.0* = 13	(35x10x10)x4 + (5x5x20) x3*	2.5x4† = 10	(15x15x15)x4†	23	.011	29000	14.5	22	15	60	.060
140 SSPA	45-55	1.7	20x14.3 X1.27	2.3	tbd	4	0.029	363.22	2.59	3.85	3.48	11.33	0.08
150 SSPA	50-55	1.5	24x16x16	2.5	tbd	4	0.027	6144	40.96	4.12	3.73	11.85	0.08

To date, spacecraft prime power has limited the radiated RF power to 10 to 100 watts, a level achieved by one SSPA at UHF and L-band or one TWT at S-band and above. However, future spacecraft power systems will provide much higher available power. Both TWTA and SSPA can use some form of power combining technology to achieve higher output power than is available from a single amplifier. The two key design parameters are the number of active amplifier devices and the method of net output power combining. Array feed architectures represent an elegant class of power combiners. There are at times close relationships among an antenna feed system, its fine pointing mechanism, and its power combining technology. The next two sections first discuss the issues confronting the current technology and then explore emerging technologies capable of meeting the requirement for Gbps-class RF communications system at TRL 6 by the year 2020.

5. Power Amplifiers Today

The key design issues for a high power amplifier are output power, efficiency, and mass and cooling (heat dissipation). TWTAs consist of a traveling-wave tube (TWT, a microwave vacuum tube) and a high voltage power supply. SSPAs have no high voltage requirements but require large current flows. As a rule of thumb, at the present state of the art a single TWTA will produce one to two orders of magnitude more RF output power than a single SSPA.

Heritage TWTs for interplanetary space communication employ helix slow wave circuits. Mars Reconnaissance Orbiter, launched in 2005, carries the two highest-power transmitters on any interplanetary spacecraft, a 100-W X-band TWTA and a 35-W Ka-band TWTA. In the laboratory, Ka-band technology has advanced to a 180-W TWT [7]. These TWTs have all incorporated helical slow-wave circuits valued for their optimum combination of efficiency, bandwidth, and low operating voltage. Slow wave circuits achieve wide bandwidth at low beam voltage by minimizing the volume of metal constraining the electromagnetic modes in the slow wave circuit. The basic physics—metal accommodates heat flow but excludes RF waves—implies the well-known inverse relationship between ruggedness and bandwidth in slow-wave circuits. The maximum power from a traditional space helix Ka-band TWT is estimated to be between 300-500 W within the foreseeable future. Power combining is needed to exceed this transmit power level.

Power level for SSPA is much lower. A Ka-band SSPA has been shown to generate tens of watts in laboratory tests by utilizing multistage combining of N >10 devices. It is predicted that this technology will be capable of achieving up to 450 W in a space demonstration by 2020.

6. Emerging Power Amplifier Technologies

Slow-wave circuits more rugged than helices sacrifice bandwidth because the increased volume of rugged metal tightens the boundary conditions on the electromagnetic field. This relationship extends from fragile helices and their cousins (the ring-loop and ring-bar circuits) to sets of coupled resonant cavities, i.e. the coupled cavity TWT (CCTWT). CCTWTs have excellent efficiency and power handling ruggedness, but they operate at a higher beam voltage than a helix TWT for a comparable percentage bandwidth. This reduced bandwidth is acceptable at Ka-band where a CCTWT operating at modest voltage still has a bandwidth greater than the full deep-space allocation (31.8-32.3 GHz). Work at JPL [8] has demonstrated the feasibility of a 1-kW, Ka-band, coupled-cavity TWT with 1-GHz bandwidth at a cathode voltage of 18 kV, a voltage that existing military, space-qualified, high-voltage power supplies can reach. Higher cathode voltage could produce 2.5 kW.

In the long term, vacuum amplifiers with multiple electron beams may provide 10 kW or more from a single compact device (e.g., multi-beam coupled-cavity TWT). Although the most advanced work is directed toward megawatt-class klystrons for accelerator applications, space borne multibeam beam amplifiers may offer reduced system mass and complexity over power-combining approaches devices whenever spacecraft prime power outstrips the maximum feasible high voltage. Advanced magnetic materials such as samarium cobalt can theoretically provide permanent magnet focusing of multiple beam devices within acceptable weight limits. For applications above Ka-band, most rugged of all are advanced klystrons including multi-beam and extended interaction klystron circuits.

SSPA development [9,10] has recently focused on wide bandgap semiconductors such as Gallium Nitride (GaN), Silicon Carbide (SiC), and other III-V based devices. The DOD, the Missile Defense Agency (MDA), and DARPA under its Wide Bandgap Semiconductor Initiative, are sponsoring research. The business sector's investments in these technologies for the cellular and base station markets may reach commercial insertion within five years.

Wide bandgap semiconductors are inherently rugged (high operating voltage, large bandwidth, high radiation tolerance and high power density), potentially making them superior to current GaAs and LDMOS (Lateral Diffused Metal-Oxide-Semiconductor) high-power amplifiers at millimeter-wave frequencies. Some key performance metrics for Ka-band GaN technology are listed below.

- Single devices have demonstrated 1-3 W, MMICs at 5-10 W, with demonstrated efficiencies ranging from the upper 30% to over 50%
- GaN device-level power densities exceeding 10 W/mm at 10 GHz have been demonstrated, whereas GaAs power density is limited to approximately 1.5 W/mm at 10 GHz. Power densities of at least 5-10 W/mm are being reported at Ka-band.
- GaN devices should be able to operate at extremely high temperatures (> 250 C). GaAs devices have an effective limit of approximately 150 C.
- GaN devices have higher RF output impedance, implying greater power-bandwidth products, and consequently possessing bandwidth inherently wider than that of GaAs-based amplifiers.
- GaN devices have 2.5 times the bandgap energy and 3 times higher electron saturation velocity than GaAs. This can permit GaN devices to operate at voltages up to almost 100 V, a good match to spacecraft prime power systems.

Microwave power modules (MPMs) represent another potential approach to achieving high RF output power. An MPM is a multi-stage amplifier that achieves most of the gain in the SSPA while adding 90% of the power with a TWT stage. This not only allows the TWT to be a physically shortened and lightened but may improve its stability to the point that severs are unnecessary. The MPM then becomes a two-mode transmitter: with the high voltage off the SSPA signal passes through the TWT with little attenuation, but when high power is needed the TWTA boosts the signal 10dB. Since its first demonstration in 1993, the MPM has found application in military airborne systems, but to date has not been used in space.

7. Power Combining

As discussed in the preceding section, the number of power amplifiers chosen to reach the required power may depend on the size and feed architecture of the antenna. Where electronic beam steering is required, for a large phased array or just for fine beam pointing, it is obvious and elegant to imagine matching the multiple antenna feeds one-to-one with the power amplifiers; yet some missions will require power combining to a single antenna feed. One would also wish to co-locate each power amplifier with its feed to eliminate long runs of high power waveguide; yet interplanetary spacecraft that must frequently reorient usually have tight constraints on the moment of inertia. Here we discuss briefly power combiners, waveguide, and by extension other components in the transmit chain between the power amplifier and the antenna feed.

Classical binary combiners such as the Wilkinson type, though well understood and effective in many applications, will not provide the needed system efficiency to allow solid-state systems to scale to TWTA power levels (120-150 W) at Ka-band. For example, a binary combiner for 20 devices (5-stages) with .4dB loss per stage wastes 37% of the input power. Novel power combining schemes are

being developed to yield SSPAs with 40% efficiency [11] at these power levels. Low loss power combiners producing up to 10x improvements in insertion loss across 10-15% bandwidths at Ka-band have been demonstrated.

Hardware demonstrations based on waveguide radial and waveguide binary combiners have shown that the output loss of a Ka-band combiner can be reduced to less than the 1–1.5 dB required to achieve an SSPA efficiency of 40% with high-efficiency GaN MMICs. As an example, using a septum combiner, a 120-W class Ka-band amplifier with 40% PAE is feasible using waveguide binary combining [11]. Additional work is being pursued to expand the combining of multiple 120-W class amplifiers into a 1-kW class solid-state transmitter for terrestrial applications.

Five power combining approaches for achieving 1 kW over the DSN frequency band were recently considered under various NASA research projects:

- binary magic-T hybrid junction
- magic-T hybrid coupler (N > 2)
- radial waveguide structures
- spatial power combining
- array feeds, including feed horn arrays and phased arrays

Of these, spatial power combining and array feeds hold promise of reliability in 10-kW systems [1]. Above 1 kW, any Ka-band waveguide network must be kept short and simple. Indeed, the antenna geometry may be limited by the need to place the feed horn(s) adjacent to the high power amplifier(s). For any downlink transmitter above 1 kW, or even above a few hundred watts, reliability concerns dictate keeping all spacecraft structures far from regions of high RF power density. This caution includes waveguide components, which are no more immune than any other surface to overheating, arcing or multipactor phenomena.

As an example, we evaluated the maximum distance between heat sinks for several models of Ka-band waveguide, assuming that the maximum tolerable temperature rise is 200C. Standard WR-28 waveguide, (0.65dB/m loss, 25mil wall thickness) carrying 10 W overheats if the heat sinks are more than 20cm apart. A proprietary low-loss waveguide, (0.11dB/m, 100mil wall thickness) produced for satellite communications applications by Antennas for Communications, Ocala FL, cannot carry 1kW for 20cm without overheating. Thermal issues are significantly reduced by placing the high power amplifiers directly adjacent to the antenna feeds; this is true for both vacuum and solid-state amplifiers.

8. Summary

The most promising deployable technology in the short term is a mesh reflector. Of the mesh reflector options, AstroMesh appears to offer the best combination of characteristics (stowage, mass density, bandwidth, etc.). However, as observed earlier, it remains to be proven that any mesh reflector will operate with sufficiently high efficiency at Ka-band. Despite their advantages, mesh reflectors rely upon a relatively complex deployment mechanism both for the reflector to “bloom” and for the boom system to position the antenna and feed, which ultimately limits S/C accommodation options.

Solid Surface Deployable antennas have demonstrated the capablity to operate at Ka-band or higher in several laboratory demonstrations. Although there are no truly compelling examples in the open literature, this class of antenna has clear advantages in surface accuracy, survival lifetime in radiation, thermal stability and bandwidth. There are two categories of inflatable antennas: true doubly curved reflectors (e.g. paraboloids) and flat membrane antennas. Both of these offer great potential for compact stowage, including an integrated feed support structure. Further, the relatively simple deployment mechanism should be more easily adaptable to spacecraft accommodation than are traditional mechanical antennas. Only a few inflatable antennas have been demonstrated, but their advantages are sufficiently compelling to warrant continued development.

The key design issues for a high power amplifier are output power, efficiency, mass, and heat dissipation. Today, a single TWTA will produce one to two orders of magnitude more RF output power

than a single SSPA. However, technology advances (e.g. wide-bandgap semiconductors) suggest that future SSPAs may rival today's TWTs in output power and efficiency. Both amplifier technologies can benefit from some form of power combining to achieve output power higher than is available from a single device. Power combining can be implemented in a waveguide, but can also be quasi-optical. Interplanetary spacecraft carry as much as a 35-W Ka-band TWTA, but there are laboratory demonstrations of Ka-band 180-W TWTs. The feasibility of a 1 kW or even 2.5 kW Ka-band coupled-cavity TWTs has been cited. In the long term (2020), single device technology may achieve up to 10kW. For the foreseeable future transmitted power above a few kilowatts will require power combining, e.g. magic-T alone or magic-T/hybrid combinations. Solid-state devices (GaN and GaAs) now achieve 1-10 W, with demonstrated efficiencies of 30–50%, and the ability to operate at extremely high temperatures (>250OC) vs. Using a septum combiner a 120-W class Ka-band amplifier is feasible, work being pursued to combine of multiple 120-W class amplifiers into a 1-kW class solid-state transmitter continues.

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