Advanced CubeSat Antennas for Deep Space and Earth Science Missions: A review

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A Review of CubeSat Antennas: From Low Earth Orbit to Deep Space

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***Abstract*—Small satellites provide low cost access to space and they have historically been used for flight technology demonstrations and limited function space science activities. Novel antenna technologies have enabled high performance smallsat telecom, science in earth orbit, and the first Cubesat mission to Deep Space. Over the past 5 years, technologists at the Jet Propulsion Laboratory have designed, tested and successfully flown these innovative and enabling Smallsat antennas. This paper describes these innovations and their impact on smallsat performance for recent and future NASA missions.**

***Index Terms*—Antenna, CubeSat, Deep Space, Low Gain antenna, LGA, High gain antenna, HGA, metasurface, patch array, loop, deployable, circular polarization.**

I. A New Era For CubeSats

FOR the past 20+ years, CubeSats have been constrained to Low Earth Orbit (LEO) applications. One of the limiting factors preventing CubeSats from venturing into deep space to explore our solar system is the size constraint of each subsystem, available DC power, and non-availability of sufficiently large RF aperture for communication and science payload [1]. In LEO, CubeSats employ a UHF deployable dipole or S-band patch antenna, as low gain is sufficient to communicate with the large ground stations. For comparison, a LEO spacecraft may have maximum communication range of only 2,000 kilometers; whereas a deep space mission must support at least a 2 million km link back to earth. [2]. Since CubeSat RF output power resources are limited, e.g. 5 watt RF, a higher gain antenna is needed to compensate for the factor of 1000 increase in range.

Extensive work was carried out at the Jet Propulsion Laboratory (JPL) to develop new low-, medium-, and high-gain antennas primarily for deep space communication at X- or Ka-band. With the recent success of two major NASA CubeSat missions, Mars Cube One (MarCO) [1] and Raincube [3], one can expect the use of CubeSats to explode in the near future.

The two MarCO 6U twin CubeSats successfully carried out their mission using a deployable X-band reflectarray and the Iris radio. They are the first CubeSats to travel into deep space and provide communication at Mars distances (~1AU) from Earth - relaying real time telemetry data from the Insight spacecraft during the Entry, Descent, and Landing (EDL) phase.

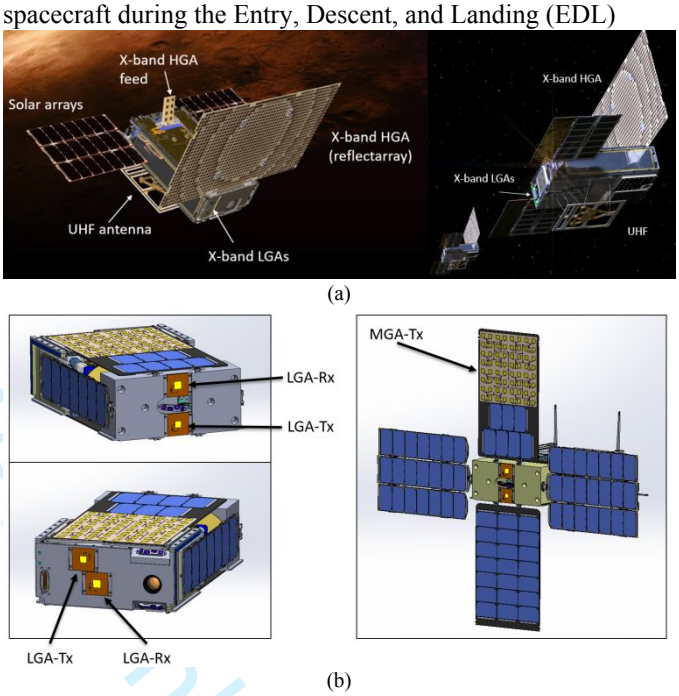

Fig. 1. Examples of Deep Space CubeSats. (a) Mars Cube One (MarCO) [1]: the first deep space CubeSats uses 4 LGAs, a HGA, and a UHF antenna. (b) Near-Earth Asteroid Scout (Nea Scout) CubeSat employs 4 LGAs and one MGA.

The RainCube mission, the first active radar in a CubeSat, deployed successfully in Low Earth Orbit (LEO). It uses a 0.5-m mesh reflector on a 6U CubeSat to measure rain and snow precipitation [3]. MarCO and RainCube could pave the way for a new generation of small spacecraft that would make interplanetary space science and high performance Earth Science much more accessible. For example, 13 deep space CubeSats (e.g. Biosentinel, Nea Scout, CuSP, Lunar Flashlight, etc.) are in development and scheduled to launch with the Exploration Mission-1 (EM-1) in June 2020 using much of the same communication capability as MarCO.

This paper will provide an overview of all existing antennas that have been used or could be used on future Deep Space CubeSats. An emphasis is made on X-band and Ka-band antennas as these are the commonly used deep space frequency

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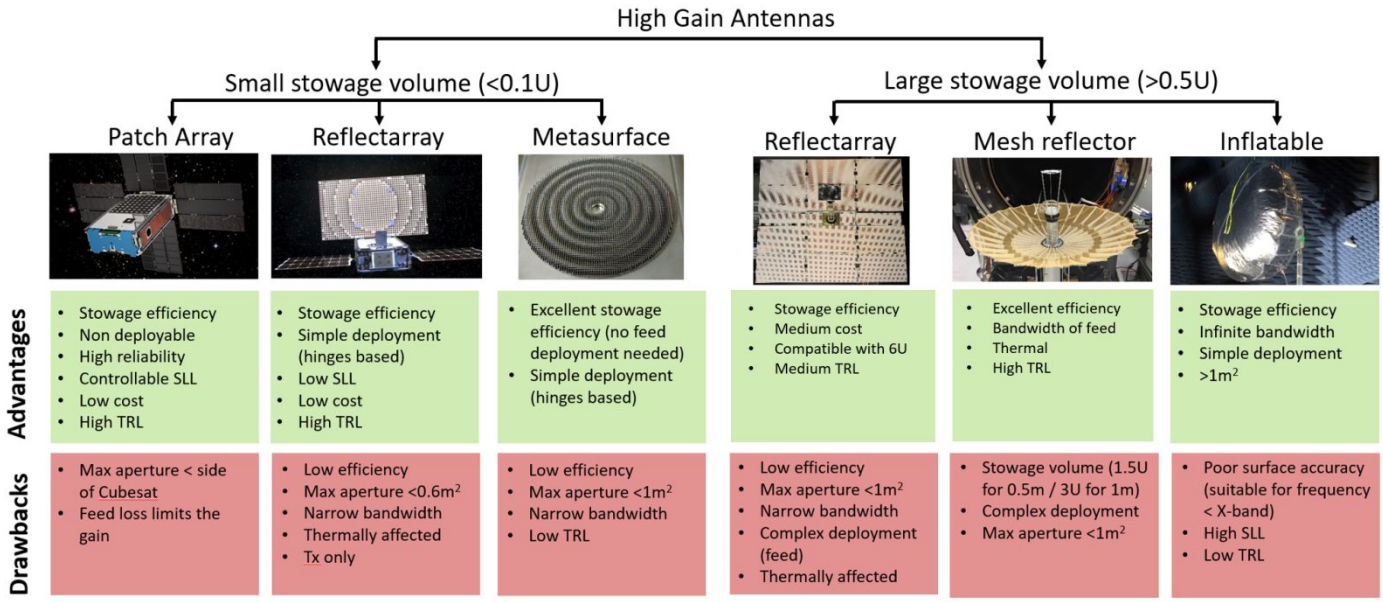


Fig. 2. High gain antenna selection guidelines for X- or Ka-band application for CubeSats.

TABLE I
ALLOCATED DEEP SPACE NETWORK FREQUENCY BANDS

Frequencies in MHz	Uplink (Earth to space)	Downlink (space to Earth)
X-band	7145–7190	8400–8450
Ka-band	34200–34700	31800–32300

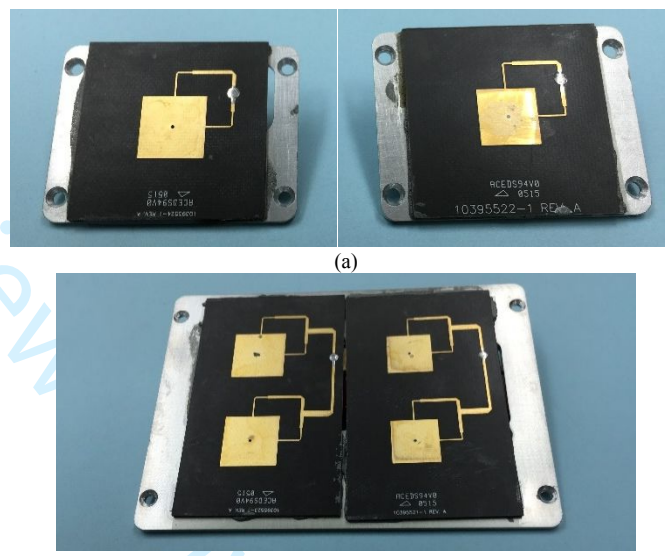
* for spacecraft at distances greater than 2 million km from Earth

bands but we are also including an overview on UHF, S-band, and Ku-band antennas. Clear guidelines to select the high gain antenna technology are provided and the measured performance of each antenna type are reported. Future research directions for CubeSat high gain antennas are also suggested. This paper is organized as follows. An overview of low-, medium-, and high-gain antennas is provided in Section II. An emphasis is given to high gain antenna performance in terms of gain and efficiency. Concluding observations are made in Section III.

II. DEEP SPACE CUBESATS

Prior to MarCO, the application of CubeSats to Deep Space was a dream and seemingly impossible with only a few institutions actively pursuing the associated technical challenges. Deep Space CubeSats, operating at a range to Earth of greater than 2 million km, are now well defined and multiple missions use a very similar communication architecture. For the sake of illustration, two Deep Space CubeSats are shown in Fig. 1. Existing Deep Space CubeSat use low gain antennas (LGAs), medium gain antennas (MGAs), and high gain antennas (HGAs) operating at X-band. To receive commands and transmit telemetry back to Earth, they need to operate at X-band or Ka-band with the Deep Space Network; the Deep Space frequency bands are summarized in Table I [2].

While, LGAs and MGAs are very straight forward (i.e. patch antennas or patch array), the choice of HGAs is less obvious and requires careful thinking. To maximize the success rate of CubeSats, mechanical deployment should only be used when needed and its complexity should be minimized when used. Fig. 2 summarizes existing HGA technologies and provides guidelines on how to select them.



(a)

(b)

Fig. 3. X-band low gain antennas for Deep Space CubeSats.

A. *Low gain antenna*

X-band LGA

Because of their larger beamwidth, LGAs provide low data rate telemetry capability without the precise pointing required by the narrow beam HGA. They can also be used for emergencies when spacecraft pointing may not be correct. LGAs are required for emergency communication near earth in case the spacecraft attitude is unknown due to an onboard anomaly.

Through a single patch antenna, the spacecraft can receive commands at 62.5bps (i.e. minimum data-rate handled by Iris V2 [4]) from a 34m DSN ground station with a pointing of ±90° at a maximum distance of 0.3AU. Still, through a single patch antenna, the spacecraft can transmit telemetry to a 70m DSN ground station at 62.5bps, with a pointing of ±90° at a maximum distance of 0.15AU.

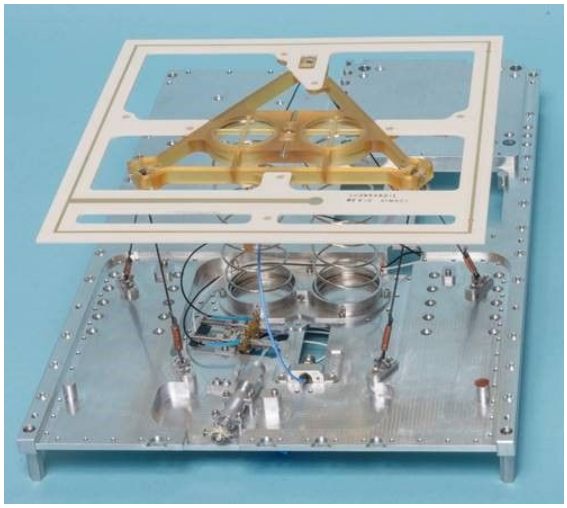


Fig. 4. Deployable MarCO UHF circularly polarized loop antenna.

In all deep space CubeSats, all antennas are either Rx or Tx due to the simple RF signal path architecture that does not use a diplexer [4]; the Iris V2 radio accommodates this non-duplex architecture with 3 ports for Tx and 2 ports for Rx. The LGAs flown on MarCO are shown in Fig. 3. They consist of dual edge-fed circularly polarized patch antennas. The two right handed circularly polarized (RHCP) patch antennas are printed on RT Duroid 5880 (ε_r=2.2 and thickness=0.787mm).

In some particular cases, more gain could be required to close the link at larger distances or to achieve higher data rates. On MarCO, higher gain was required in the same pointing direction as its reflectarray (i.e. 22.7° from the bus axis). Patch arrays are a simple option to achieve higher gain at a given direction. The MarCO LGAs are primarily used at Mars distance to receive commands (and to transmit telemetry in case of the HGA malfunction) while the spacecraft is pointed to achieve its primary goal — relay EDL telemetry data of Insight lander — consist of 2×1 patch arrays (see Fig. 3b). The 2×1 patch arrays provide a gain greater than 7dBic within 22.7°±8 from the bus axis.

Most deep space missions, such as Nea Scout or Biosentinel, require full coverage using LGAs. In such cases, two single patches are used on each side of the CubeSat (see Fig. 1b).

UHF LGA

UHF antennas are heavily used for LEO CubeSat communication [5]-[11] and are commonly used for surface-to-orbit relay communications at Mars. MarCO's prime mission was real-time relay communication support for the InSight lander so a UHF antenna was required. [1].

The most commonly used UHF and VHF antenna for LEO cubesats is the commercially available ISIS deployable system, which consists of one or more measuring tape springs of up to 55 cm each in length [5]. Various antenna configurations are available (monopole, dipole, or turnstile) for linear or circular polarizations with an omnidirectional pattern and a gain of about 0dBi. For higher gain, other antennas have been investigated for UHF operation such as loop antennas [6], [7], helical antennas[8]-[12], and patch antennas [13].

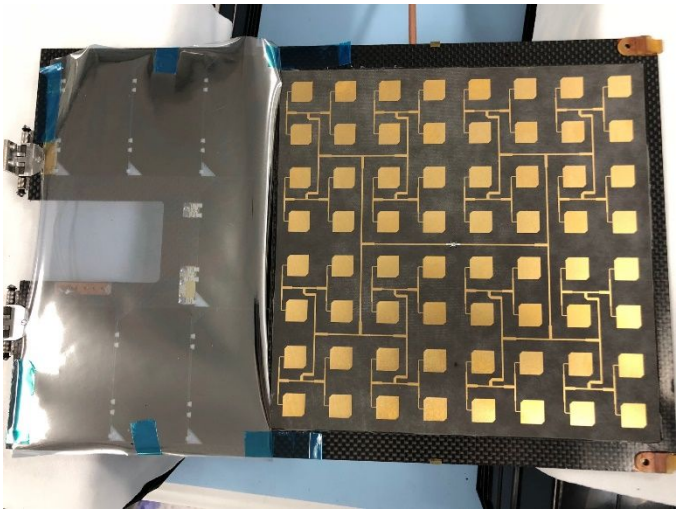


Fig. 5. NeaScout X-band medium gain antenna located near solar cells. The 8×8 patch array is mounted on a carbon fiber deployable wing. The same antenna is used on other Deep Space missions (Biosentinel, CuSP) with different locations.

For MarCO, to receive the EDL telemetry from Insight, an antenna gain of 5dBi (>0dBic at ±30degree off boresight) was needed [1]. The chosen approach was a deployable loop, fed at two locations, each generating orthogonal linear polarization 90 degrees out of phase with the equal amplitude, and thus giving rise to circular polarization. The antenna is shown in Fig. 4.

B. Medium gain antennas

As illustrated in Fig. 2, patch arrays are very attractive antennas when they can fulfill the gain requirement without involving any complex mechanical deployment. They are constrained to the maximum size of the CubeSat. On a 6U-class CubeSat, an 8×8 patch array can easily fit. Missions such as NeaScout, Biosentinel, CuSP, are all using a transmit-only 8×8 circularly polarized patch array providing more than 23.4dBic which achieves 1kbps at 1AU using a 34m DSN antenna or 4kbps using a 70m DSN antenna. The medium gain antenna developed for NeaScout is shown in Fig. 5.

More recently, a new all-metal patch array was developed for a potential Europa Lander [14] (see Fig. 6). This antenna demonstrates unprecedented efficiency of more than 80% and the 8x8 patch array achieved a gain of 25.3dBic, supporting both uplink and downlink frequency bands. This resulted in a 2dB improvement compared to the previous array, which translates into a 1.6 times data rate improvement. One drawback of this antenna is the mass increase but to mitigate that one can consider using the spacecraft bus as the ground plane.

The first metal-only metasurface antenna was fabricated using metal additive manufacturing [15] (Fig. 7). It is operating at Ka-band in the downlink DSN frequency band (i.e. transmit only). The 10cm-diameter MTS antenna achieves 26.1dBic. Such an antenna can be printed on the bus surface using the largest side of the CubeSat as a radiating aperture. Unfortunately, they are still low efficiency (~<40%). However, it was recently published that MTS antennas can possibly achieve up to 70% efficiency [16]. This would make them good candidate for transmit-only MGA antennas at X- or Ka-band, particularly because they can be designed to achieve any

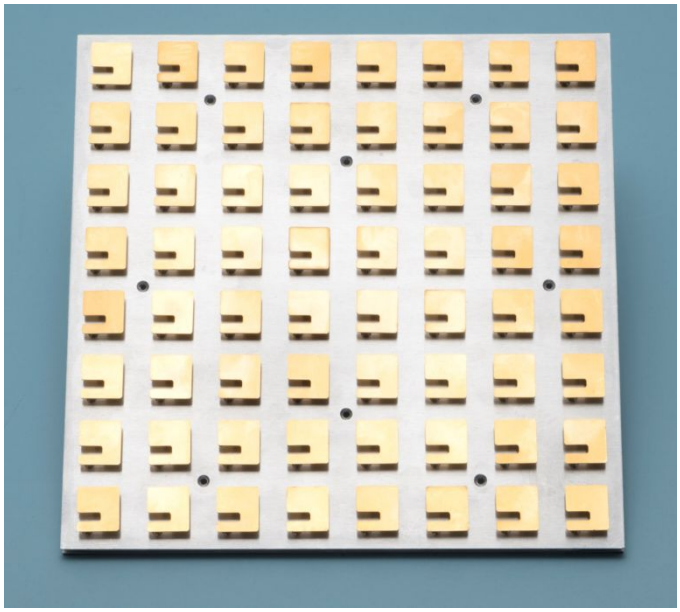


Fig. 6. All-metal dual-band RHCP X-band 8x8 patch array [14].

Fig. 7. Metal-only RHCP Ka-band metasurface antenna [15].

radiation pattern (i.e. directive, isoflux, etc.).

C. High gain antennas

High gain antennas for telecommunication applications that produce narrow beamwidths for Earth or Planetary science needs, are crucial for CubeSats. They enable CubeSats to venture into Deep Space and still provide high volume science return. Multiple HGA technologies have been actively developed: reflectarrays [20]-[21], mesh reflectors [24]-[32], and inflatables [33]-[36]. Other applicable HGA technologies such as membrane antennas [37]-[41], slot arrays [42],[43], and metasurface [15]-[17] will also be discussed in this Section.

Reflectarrays

In 1996, John Huang introduced [18], [19] the idea of using deployable reflectarray composed of flat panels that could also potentially be combined with solar cells in the back of the reflectarray. This concept takes advantage of flat reflecting surface relying on a simple mechanical deployment with spring loaded hinges [18]. His concept was implemented for the first time for the technology demonstration CubeSat ISARA (Integrated Solar Array & Reflectarray Antenna) [20]. The

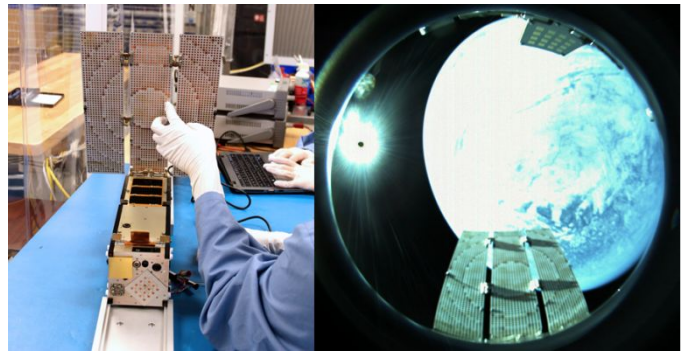


Fig. 8. (Left) NASA's JPL ISARA CubeSat during Integration and Testing. (Right) Photography of ISARA reflectarray successfully deployed in-orbit [20].

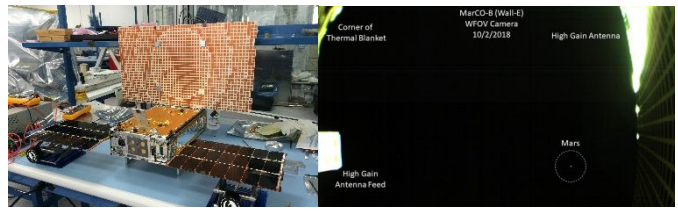


Fig. 9. (Left) NASA's JPL MarCO CubeSat during Integration and Testing. (Right) Photography of MarCO HGA successfully deployed in-orbit [1],**Error! Reference source not found.**.

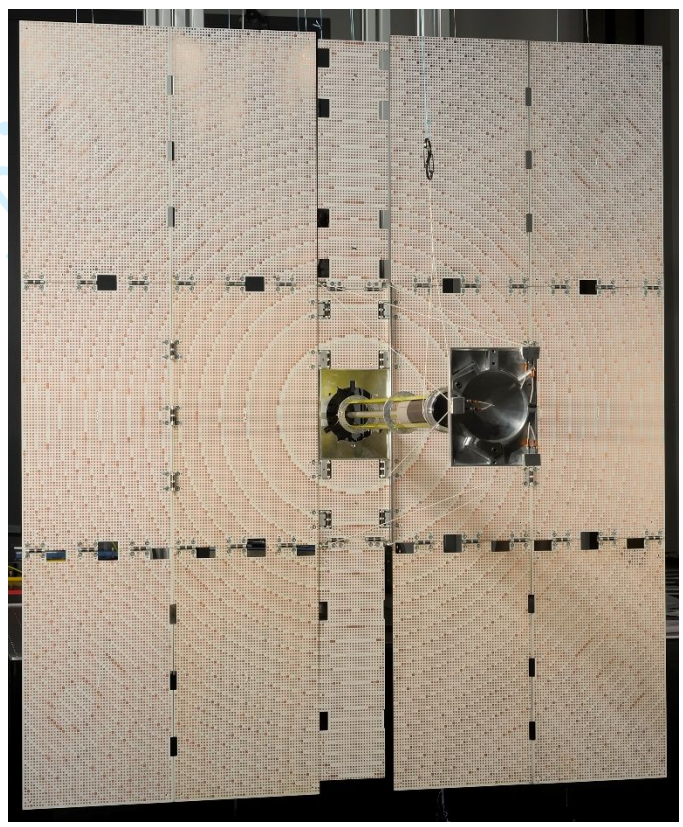


Fig. 10. One-meter reflectarray antenna (OMERA) compatible with a 6U-class CubeSat [21].

ISARA is the first reflectarray in space. It demonstrates a gain of 33.0dBic at 26GHz for Low Earth Orbit communication, which translates into an efficiency of 26%. It suffers from a low efficiency feed and large gaps and hinges, resulting in an increase of the side lobe level and reduced gain. The antenna was successfully deployed in orbit as witnessed by

the photography of the deployed antenna taken in-orbit (Fig. 8)

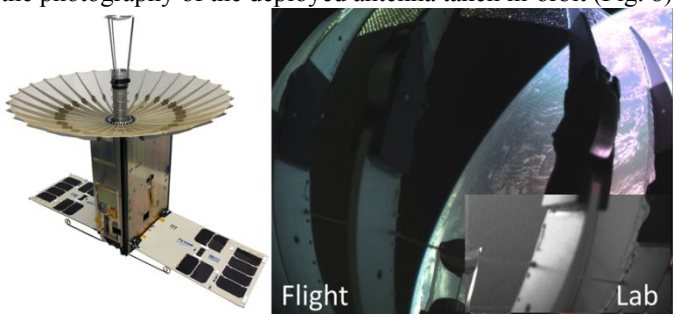


Fig. 11. NASA's JPL 0.5-m mesh reflector antenna on Raincube CubeSat [27] was successfully deployed and operated in-orbit.

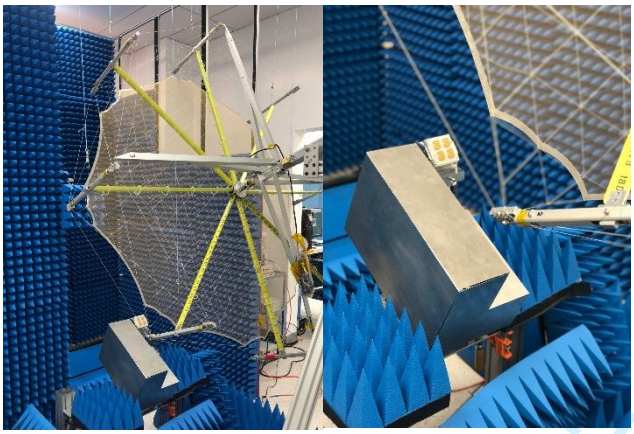


Fig. 12. One-meter deployable mesh reflector for deep space communication at X-, Ka-, or X/Ka-band [32]. The mesh reflector mechanical deployment is described in [31].

and measurement from the ground. The project demonstrated on-orbit operation of the combined solar arrays and reflectarray.

This work was extended to an X-band telecommunication system using a reflectarray deployed from the 6U CubeSat, launched as a secondary payload with the NASA InSight Mars lander mission to provide auxiliary telecommunications during the EDL portion of that mission [1],[21]. The transmit-only reflectarray demonstrates a gain of 29.2dBic (i.e. 42% efficiency). Higher efficiency was achieved by (1) removing the gaps between the panels, (2) using low profile hinges. (3) improving significantly the feed efficiency. MarCO near-real time bent pipe communication (i.e. 8kbps) at Mars distance (~156 million km) would have not been possible without this X-band deployable reflectarray as the Iris radio solid state power amplifier (SSPA) is limited to 5W [1],[21]. For MarCO, the choice of deployable patch array HGA technology was driven by the need for large physical aperture size to stow in the very limited volume available inside the bus. A photography of the deployed antenna is shown in Fig. 9 while the CubeSat is approaching Mars. The antenna gain of MarCO reflectarray performed within 0.4dB of its design value during Insight EDL and provided flawless near-real-time coverage.

To achieve a smaller beamwidth for remote sensing science applications, a deployable reflectarray antenna compatible with 6U-class CubeSat was developed [21]; it is currently the largest Ka-band cubesat-compatible antenna. While this antenna was designed primarily for Earth Science remote sensing [21], it can easily be redesigned for Deep Space communication. The Ka-band high gain reflectarray antenna employs

Fig. 13. S-band deployable membrane antenna after its first deployment [40].

Cassegrainian optics to accommodate a deployment mechanism that stows the reflectarray panels and feed assembly into a highly constrained volume. Despite stringent Ka-band small wavelength mechanical constraints, the linearly-polarized antenna demonstrates excellent performance at 35.75GHz with a gain of 47.4 dBi [21].

Mesh reflector

Multiple deployable mesh reflector for CubeSats were developed at S-band [24],[25], X-band [26], or Ka-band [27]-[30].

A Ka-band 0.5m deployable mesh reflector compatible with 6U-class CubeSat was introduced for deep space communication [27] and Earth science mission [28]. Although the antenna fits in a constrained volume of 1.5U (i.e. $10\times10\times15cm^3$) a gain of 42.4dBi and a 56% efficiency were demonstrated. The antenna was successfully deployed in LEO on July 28, 2018 (see Fig. 11). The mechanical deployment is thoroughly described in [29].

An offset mesh reflector compatible with 12U-class CubeSats is currently under development at Tyvak [32]. The offset configuration enables a higher efficiency (no feed blockage), achieves lower side lobe levels and as most reflector type antennas is directly applicable to other or multiple frequencies. The antenna was designed at X- and Ka-band for deep space communication [32] (Fig. 12). For X-band, a gain of 36.1-dBic and 36.8-dBic is achieved at uplink and downlink frequency bands, respectively (i.e. ~72% and 62% efficiency, respectively). At Ka-band, a gain of 48.4-dBic is obtained at downlink frequency band (~62% efficiency). The mechanical deployment is still in progress but the results are promising.

Inflatables

Inflatable antennas were developed and comprehensively tested at S-band [33] and X-band [34] for Deep space communication. Additional work was also reported by another team at W-band [35]. Although the spherical surface aberration can be compensated by adjusting the feed location [34],[35] or using a corrective lens [36], it is unlikely that the surface accuracy can be maintained at frequencies above S-band.

TABLE II
DEPLOYABLE HIGH GAIN ANTENNA PERFORMANCE FOR CUBESATS

Name	Type	Aperture size	Frequency	Gain	Efficiency**	CubesSat size
ISARA [20]	Reflectarray	0.33m×0.27m	26 GHz	33.0 dBic	26%	3U
MarCO **Error! Reference source not found.**	Reflectarray	0.60m×0.33m	8.4 GHz	29.2 dBic	42%	6U
OMERA [21],[23]	Reflectarray	1.05m×0.91m	35.75 GHz	47.4 dBi	32%	6U
KapDA [28]	Mesh reflector	0.5m diam.	32 GHz 34 GHz	42.0 dBic 42.4 dBic	57% 55%	6U
KaTENna [26] *	Mesh reflector	1m diam.	8.4 GHz 35.75 GHz	36.8 dBic 48.4 dBic	62% 62%	12U
Membrane [40] *	Membrane	1.24m×1.24m	3.6 GHz	28.6 dBi	18%	6U
LaDeR [41] *	Membrane	1.5m×1.5m	8.4 GHz	39.6 dBi	40%	6U

* not fully completed - with missing elements that will affect the gain and efficiency
** The efficiency is defined as the ratio of the realized gain of the antenna to its standard directivity. The standard directivity is $4\pi A/\lambda_0^2$, where A the area of the antenna aperture and λ_0 is the free space wavelength. This defines how efficiently the area of an antenna is used.

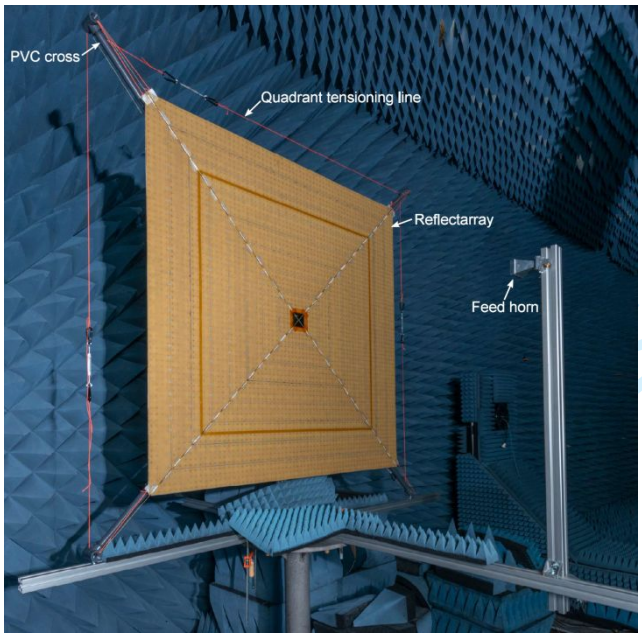


Fig. 14. Deployable membrane reflectarray currently in development at JPL [41].

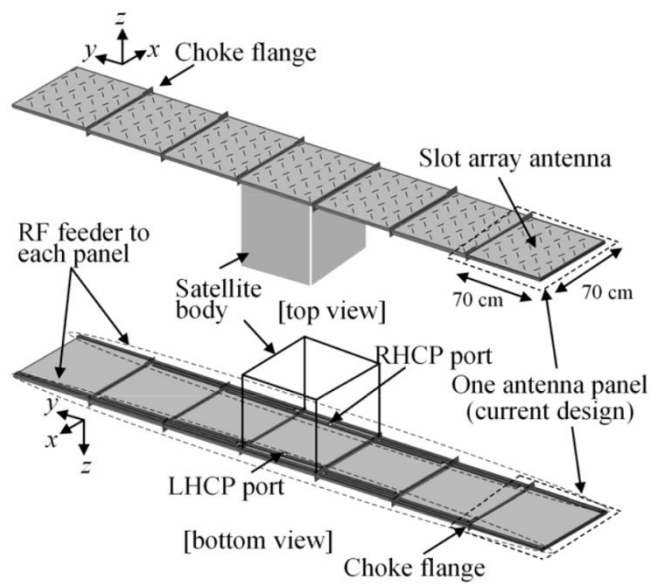


Fig. 15. X-band deployable slot array for small satellite with 55% efficiency [42][43].

Membrane antennas

Membrane antennas were highly investigated by John Huang [37]-[39] at the Jet propulsion Laboratory for small satellites as they allow achieving large aperture with excellent stowage volume. Membrane antennas can be patch arrays [37] or reflectarrays [38],[39] and are a natural option for CubeSats. A large patch array operating at S-band was recently introduced for 6U-class CubeSat [32] (Fig. 13). A 1.53m^2 linearly-polarized patch array deploys from a 2U stowage volume. After multiple deployments, a 28.6dBi gain was measured which translates into an 18% efficiency.

A X-band reflectarray membrane antenna is under development at the Jet Propulsion Laboratory [41] (Fig. 14). It deploys into a 1.5m^2 aperture with a 0.5mm surface rms from a canister of 20cm diameter and 9cm height. A gain of 39.6dBi was measured using a feed horn located at its focal point. Although this is not the complete antenna, the efficiency achieved is about 40%. The feed deployment inaccuracy, feed efficiency, and feed blockage will incur additional losses.

Slot arrays

The concept of a deployable slot array was presented for 100kg small satellites [42]. It consists of six deployable panels folding around the spacecraft (Fig. 15). Slot arrays are good solutions for single-band and narrow-band applications with linear or circular polarization. The concept introduced in [42] can be implemented for CubeSats at Ka-band or above.

Reference [43] presents the development of an S-band slot array able to produce three operating modes: omnidirectional, multibeam, or directive.

Metasurface antennas

Metasurface antennas could potentially also be a good solution for high gain antennas. They provide the ability to deploy a large aperture antenna without deploying a feed at a focal distance from the antenna aperture. Feed mechanics and geometry is often the biggest challenge as antenna aperture increases and in particular for deployable antennas. [21],[23].

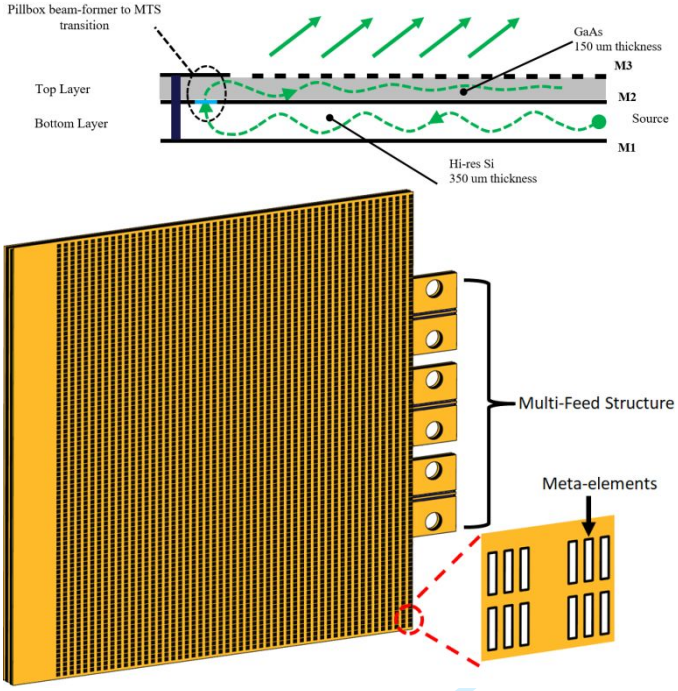


Fig. 16. W-band beam steering metasurface antenna under development at JPL.

Similar deployment approaches for deployable reflectarrays can be applied. From 6U- or 12U-class CubeSats, the maximum aperture achievable is about 1m^2. The effect of small gaps between the panels remains to be assessed. As mentioned earlier, metasurface antennas are narrow band. A methodology to achieve dual-frequency operation from the same aperture was recently reported [44],[45].

A silicon (Si) and gallium arsenide (GaAs) semiconductor based holographic metasurface antenna operating at 94 GHz is under development at JPL (Fig. 16). The metasurface antenna achieves beam-forming in a holographic manner; involving the modulation of a guided-mode reference with a metasurface layer to produce the desired radiation wave-front. The Si/GaAs metasurface antenna has multiple surface-integrated-waveguide (SIW) feeds and a quasi-optical feeding structure, enabling beam steering in the elevation direction by means of switching between the SIW feeds [46],[47]. The antenna is currently under fabrication and will be shared soon.

III. Conclusion

As small spacecraft venture from LEO to Deep Space to explore our solar system, with a quick turnaround and lower cost, new antennas are crucial to enable this historical space advancement. This paper summarizes the innovation work on CubeSat antennas ranging from low-gain to high-gain antennas operating at UHF, S-, X-, Ku-, and Ka-band. The choice of HGA technologies is not straightforward when planning a new mission and this paper provides clear examples of technology choices to achieve mission goals and constraints. A comparison table for all available HGAs is provided (Table II). On-going efforts are summarized with promising results (e.g. membrane antennas and larger mesh and reflectarray designs). Finally, new directions of research are provided for SmallSat HGAs, such as slot arrays or metasurface antennas.

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