Mars Helicopter Communication Link and Innovative Antennas for Cubesats, Landers and Rovers

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MARS HELICOPTER
Satellites Orbiting Mars Provide Large Scale Maps of the Surface from an Altitude of 200 Miles, But Finer Features Are Not Detectable.
Cameras on the “Neck” of the Rover Provide More Detailed Ground Level Imagery …… But Are Limited to Unblocked Line of Sight.
Opportunity Rover
Spent 100 Days
Roaming the Perimeter
of this Crater in Search
of Safe and Interesting
Entry Point
Curiosity Rover …
Roving Over Terrain that Should Have Been Avoided ….. If One Knew
1. First test of powered flight on another planet.

2. Built to be light and strong enough to stow away under the rover while on the way to Mars, and survive the harsh Martian environment after arriving on the surface. The helicopter weighs less than 4 pounds (1.8 kilograms).

3. Powerful enough to lift off in the thin Mars atmosphere. The atmosphere of Mars is very thin: less than 1% the density of Earth's.

4. The helicopter may fly for up to 90 seconds to distances of almost 980 feet (300 meters) at a time and about 10 to 15 feet from the ground. That's no small feat compared to the first 12-second flight of the Wright Brothers' airplane.

5. The helicopter flies on its own, without human control. It must take off, fly, and land, with minimal commands from Earth sent in advance.
**HELICOPTER ANTENNA**

![Helicopter antenna on its solar panel](image)

Antenna design:
- Fasteners (PEEK)
- Radiating element (stainless steel)
- Washers (PEEK)
- PCB (Arlon 85N)

**FM Helicopter antenna**

![Helicopter antenna Pattern with blade angle of 000 degree](image)

- Gain (dB)
- $\theta_H$ (degree)
- $E_{\phi}$

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ROVER ANTENNA

Antenna design

Antenna on M2020 Rover

Antenna testing on M2020 Rover mockup

Helicopter Base Station Antenna (HBA) radiation pattern

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Propagation Link while the helicopter is on the ground:

Map coverage assuming min, mean, max polarization loss with blade rotating.

Azimuth angle $\theta_h = [0^\circ - 359^\circ]$
Propagation Link while the helicopter is flying:
Map coverage assuming min, mean, max polarization loss with blade rotating.

- Received power of $> -99$ dBm $\Rightarrow$ 250 kbps
- Received power of $[-108, -99]$ dBm $\Rightarrow$ 20 kbps
- No link

Azimuth angle $\theta_h = [0^\circ - 359^\circ]$
FIELD TEST FOR VALIDATION

\[ L_c = 5.5 \text{dB} \]

\[ P_{\text{out}} = 28.65 \text{dBm} \]

\[ P_{\text{meas}} \]

ROVER

HELI

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WHAT ABOUT ON MARS?

First Flight performed at 63m:

- $P_{Rx\_calc} = -39.7\, \text{dBm}$
- $P_{Rx\_meas} = -37\pm 1\, \text{dBm}$

- $P_{Rx\_calc} = -51.0\, \text{dBm}$
- $P_{Rx\_meas} = -49.0\pm 1\, \text{dBm}$

- $P_{Rx\_calc} = -48.6\, \text{dBm}$
- $P_{Rx\_meas} = -48.5\pm 0.5\, \text{dBm}$
WHAT ABOUT ON MARS?

Flight 4 (in flight):
- Min distance (start and end) at 67m
- Max distance (in air) at 141m

Flight 4 - one way forward
- Measured on Mars
- Predicted (min polarization loss)
- Predicted (max polarization loss)

Flight 4 - one way backward
- Measured on Mars
- Predicted (min polarization loss)
- Predicted (max polarization loss)
WHAT ABOUT ON MARS?

Flight 5 (in flight):
- Start distance of 92m
- Max distance (end) of 128m

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Toward more accurate predictions

The Problem:
- Altair Winprop tool accounting for topology using the following methods:
  - **Parabolic Equation** (PE): uses numerical algorithms to consider propagation phenomena like reflection, diffraction, and forward-scattering. It accounts for the properties of the ground by the following parameters: (1) conductivity of the ground and (2) dielectric permittivity of the ground.
  - Inputs to this tool are the surface topology who needs to be generated (Matlab codes) and the antenna radiation pattern for the Rover and Helicopter which is generated using FEKO.

Background:
- Antenna modelling of Rover and Helicopter is critical for the validity of these analysis.
- Antenna patterns were characterized using Altair Feko as required as input for Winprop.

Summary:
- This tool was introduced to improve future telecommunication predictions in adverse scenarios by accounting for the Mars topology.
- This method was verified using the first 18 flights.
- It was then used for the rest of Ingenuity Mission Op.
Validation Using Flight 18

Flight 18:
- Take off distance of 358m
- Landing distance of 534m

Flight #18
<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt A (liftoff)</td>
<td>-686.1</td>
</tr>
<tr>
<td>Pt B (touchdown)</td>
<td>-497.1</td>
</tr>
</tbody>
</table>

Rover location
<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>-709.3</td>
<td>-534.8</td>
<td>-129.1</td>
</tr>
</tbody>
</table>

Liftoff – PE at 914MHz
- $P_{Rx\_meas} = -99\pm1\text{dBm}$
- $P_{PE} = -96.7\text{ dBm}$

Touchdown – PE at 914MHz
- $P_{Rx\_meas} = -96\text{dBm}$
- $P_{PE} = -95.1\text{ dBm}$
CUBESAT ANTENNAS
MARCO - *First Deep Space CubeSat*

Provided bent pipe communication at 1AU at 8kbps using an innovative UHF deployable antenna and the first reflectarray in Space.

**Drastic requirements:**
- Stowage volume: 12.5mm \times 210mm \times 345mm
- Gain of at least 28dBic (required aperture: 335mm \times 587mm)

**Constraints:**
- No internal stowage volume
- Limited RF output power
Reflectarray design:

Panel configuration

<table>
<thead>
<tr>
<th></th>
<th>S/N 001</th>
<th>S/N 002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computed directivity</td>
<td>30.56</td>
<td>30.50</td>
</tr>
<tr>
<td>Feed loss</td>
<td>-0.74</td>
<td>-0.74</td>
</tr>
<tr>
<td>Patch dielectric loss</td>
<td>-0.25</td>
<td>-0.25</td>
</tr>
<tr>
<td>Patch conductor loss</td>
<td>-0.04</td>
<td>-0.04</td>
</tr>
<tr>
<td>Mismatch loss</td>
<td>-0.14</td>
<td>-0.14</td>
</tr>
<tr>
<td>Hinge mounting area loss</td>
<td>-0.15</td>
<td>-0.15</td>
</tr>
<tr>
<td>Total loss</td>
<td>-1.32</td>
<td>-1.32</td>
</tr>
<tr>
<td>GAIN predict</td>
<td>29.24</td>
<td>29.18</td>
</tr>
</tbody>
</table>

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OMERA – Larger Deployable Reflectarray

Ka-band deployable reflectarray:
- 1-m reflector Ka-band antenna (98.6cm×82.1cm)
- Polarization: V-polarization
- Gain: > 47.0 dBi
- Efficiency: 47%

<table>
<thead>
<tr>
<th>Gain (dBi)</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal directivity</td>
<td>51.58</td>
</tr>
<tr>
<td>Spillover</td>
<td>50.67</td>
</tr>
<tr>
<td>Taper</td>
<td>49.95</td>
</tr>
<tr>
<td>Blockage</td>
<td>49.67</td>
</tr>
<tr>
<td>Struts</td>
<td>49.37</td>
</tr>
<tr>
<td>Gap loss</td>
<td>49.22</td>
</tr>
<tr>
<td>Patch dielectric / conductivity loss</td>
<td>48.97</td>
</tr>
<tr>
<td>Surface accuracy *</td>
<td>47.77</td>
</tr>
<tr>
<td>Feed loss / telescoping waveguide / transition</td>
<td>47.47</td>
</tr>
<tr>
<td>Feed mismatch (RL=17dB)</td>
<td>47.38</td>
</tr>
<tr>
<td>Overall performance</td>
<td>47.38</td>
</tr>
</tbody>
</table>
OMERA – Larger Deployable Reflectarray

Ka-band deployable reflectarray:
- 1-m reflector Ka-band antenna (98.6cm × 82.1cm)
- Polarization: V-polarization
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- Efficiency: 47%

Gain = 47.1 dBi at 35.75GHz
SWOT Mission
Surface Water and Ocean Topography (SWOT)
Surface Water and Ocean Topography (SWOT)

V-polarization azimuth reflectarray radiation patterns at 35.75 GHz: (a) antenna 1 and (b) antenna 2.

V-polarization elevation reflectarray radiation patterns at 35.75 GHz: (a) antenna 1 and (b) antenna 2.

More Reflectarrays – X-band

• **Features:**
  - Compatible with 6U CubeSat
  - X-band design for Telecom
  - Transmit only
  - Deployed area: 600mm × 670mm
  - Gain of 32.5dBiC between 8.4-8.45GHz
More Reflectarrays – X-band

- **Features:**
  - Compatible with 6U CubeSat
  - X-band design for Telecom
  - Transmit only
  - Deployed area: 600mm x 670mm
  - Gain of 32.5dBic between 8.4-8.45GHz

**Dual Frequency:**
- PL dual frequency feed
- Convert LP to CP by utilizing a reflectarray element that provides a relative phase shift of ±90
More Reflectarrays – Ka-band

- **Features:**
  - Compatible with 6U CubeSat
  - Ka-band design for Telecom
  - Transmit only
  - Deployed area: 600mm × 670mm
  - Gain of 43.2dBiC between 31.8-32.3GHz
More Reflectarrays – X/Ka-band

- **Features:**
  - Compatible with 6U CubeSat
  - X- and Ka-band design for Telecom
  - Transmit only
  - Deployed area: 600mm × 670mm
  - Gain of 32dBi between 8.4-8.45GHz
  - Gain of 43.5.0dBi between 31.8-32.3GHz
  - Co-located feed with identical beam-pointing

X-band elements in green ($h_x=1.5\text{mm}$)
Ka-band elements in blue ($h_{Ka}=0.406\text{mm}$)
Beam Steering
Reflectarrays
Beamsteering Reflectarrays

Beam Steering Approaches

Feed tuning
1. Single feed
2. Multiple feeds
3. Switched array
4. Phased Array
   For single or dual reflectors

Aperture Tuning
1. Mechanical Tuning (Motors, Actuators)
2. Electronic Devices (PIN, Varactors, MEMS)
3. Functional materials (Liquid crystal, ferroelectric)

Phase distribution on each element of reflectarray

\[ \phi(x_i, y_i) = -k_0 R_i + \phi_R(x_i, y_i) \]

1\text{st} term - Spatial delay between phase center of feed and element on reflectarray
2\text{nd} term - Reflection phase of \(i\)th element on aperture
Electronically Reconfigurable Unit cells

H. Luyen et.al, IEEE TAP 2022

F. Wu et.al, IEEE TAP 2021

J. Han et.al, IEEE AWPL 2019

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Electronic Beamsteering Reflectarrays

H. Luyen et al., IEEE TAP 2022

For 1 bit operation

\[
\Phi_{\text{out}}(m, n) = -\frac{2\pi}{\lambda} r_{mn} \sin(\theta_0) \cos(\phi_{mn} - \phi_0) + \phi_{\text{ref}}
\]

Desired outgoing phase

\[
\Phi_{\text{cell}}(m, n) = \Phi_{\text{out}}(m, n) - \Phi_{\text{inc}}(m, n)
\]

Phase shift of unit cell

Incident E field phase

Direction of main beam \((\theta_0, \phi_0)\)

\[
\text{Mode} = \begin{cases} 
1, & \text{if } -90^\circ \leq \Phi_{\text{cell}}(m, n) < 90^\circ \\
2, & \text{if } 90^\circ \leq \Phi_{\text{cell}}(m, n) \text{ or } \Phi_{\text{cell}}(m, n) < -90^\circ
\end{cases}
\]

Amplitude and phase distribution of incident E field from feed horn antenna on reflectarray

Non quantized and quantized phase distribution on unit cells for main beam at 30° in E plane
Electronic Beamsteering Reflectarrays
H. Luyen et. al, IEEE TAP 2022

Control circuitry

Beam steering performance

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Beamsteering Reflectarrays using MEMS

O. Bayraktar et al., IEEE TAP 2012

MEMS switch size $0.4 \times 0.14$ mm for Ka band
Continuous Electronic Beamsteering Reflectarrays

M. Trampler et.al, IEEE TAP 2020

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