The Visual Brightness of Starlink Satellites

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Dark & Quiet Skies for Science and Society II

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Visual Magnitude - A Metric for Science and Society

- **For Science**
  SatCon1 workshop report:
  Satellites fainter than V-band magnitude 7.0 can be removed from images

- **For Society**
  Visual limit is magnitude 6.0 under dark skies

- **SpaceX goal** “Making the satellites generally invisible to the naked eye within a week of launch”
Characterizing Magnitudes

- Apparent magnitude
  What you see by eye or record electronically
  Simple and directly applicable
  **Magnitude at a standard distances**
  Derived from apparent magnitudes
  550 km is the Starlink operational altitude
  1,000 km allows for comparisons

- Magnitude as a function of illumination phase angle
- Starlink brightness function
## Visual Magnitudes at Standard Distances

<table>
<thead>
<tr>
<th>Type</th>
<th>550 km</th>
<th>1,000</th>
<th>RMS</th>
<th>N</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>VisorSat</td>
<td>5.92</td>
<td>7.22</td>
<td>0.85</td>
<td>430</td>
<td>a</td>
</tr>
<tr>
<td>Original</td>
<td>4.63</td>
<td>5.93</td>
<td>0.67</td>
<td>830</td>
<td>b</td>
</tr>
</tbody>
</table>

Difference = 1.29
VisorSat 31% as bright as Original

Ref a: Mallama, arXiv:2101.00374
Ref b: Mallama, arXiv:2006.08422
Phase Function Geometry

- Sun
- Satellite
- Observer

Phase Angle ≈ 180 - Elongation

Angle at Sun << 1 degree

Solar Elongation
An Idealized Phase Function

Sunlit percent of a sphere converted to a magnitude

Magnitude (normalized at 90 degrees)

Phase Angle
VisorSat Phase Function

Magnitude (normalized at 90 degrees) vs. Phase Angle
VisorSat and Original Design Compared

[Graph showing magnitude comparison between Original Design and VisorSat Design across phase angles.]
Phase Angle ‘Characteristic’ Geometry (zenith at end of astronomical twilight)

- Satellite
- Phase Angle = 72 deg
- Observer
- To Sun, elevation = -18 deg
### Phase Angle Characteristic Magnitude

Phase angle 72 degrees

<table>
<thead>
<tr>
<th>Type</th>
<th>Mag.</th>
</tr>
</thead>
<tbody>
<tr>
<td>VisorSat</td>
<td>6.11</td>
</tr>
<tr>
<td>Original Design</td>
<td>4.81</td>
</tr>
</tbody>
</table>
Starlink Brightness Function

- Physically motivated by the shape of the satellite
- Defined in a satellite-centered coordinate system

References
Mallama, arXiv:2109.07345
Cole, arXiv:2107.06026
SBF - Physical Motivation and Coordinate System

Solar Array (back view)

Body Panel (bottom view)

Sun

Nadir
SBF Parameters

- Defined in the satellite-centered coordinate system:
- Elevation of the observer
- Elevation of the Sun
- Azimuth of the observer (relative to the Sun)
SBF Observational Data

- MMT9 robotic observatory
- Located with the Russian 6 meter telescope
- Matches V-band to about 0.1 magnitude
- 20,000 observations used in this solution
- (This processed data is available upon request)
SBF – VisorSat Apparent Magnitude
Sky Map When Astronomical Twilight Ends

Solar Elevation = -18 degrees
Solar Azimuth = 0 degrees

Apparent Magnitudes
- Red: < 5.0
- Purple: 5.0 - 6.0
- Green: 6.0 - 7.0
- Blue: > 7.0
- Black: Eclipse
SBF – Original Design Apparent Magnitude Sky Map When Astronomical Twilight Ends

Solar Elevation = -18 degrees
Solar Azimuth = 0 degrees

Apparent Magnitudes:
- < 5.0
- 5.0 - 6.0
- 6.0 - 7.0
- > 7.0
- Eclipse
Animation of VisorSat Sky Maps

Solar Elevation = -06 deg.
Solar Azimuth = 302 deg.
Latitude = 35 deg.

Apparent Magnitudes
- Red: < 5.0
- Purple: 5.0 - 6.0
- Green: 6.0 - 7.0
- Blue: > 7.0
- Black: Eclipse
Future Work

• Process and analyze 100,000 MMT9 observations
• Study changes of brightness from 2019 through 2021
• Analyze the brightness of polar orbiting Starlinks

Acknowledgments

• Richard Cole and Jeremy Tregloan-Reed for discussions and ideas
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