Satellite Coverage Analysis: Ground Coverage, Revisit Times, and Constellation Design

A Comprehensive Study of Earth Observation and Communication Systems

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Abstract

This technical report presents a comprehensive analysis of satellite ground coverage for Earth observation and communication missions. We compute instantaneous coverage footprints, revisit times for single satellites and constellations, and analyze Walker constellation parameters for global coverage. The analysis includes elevation angle constraints, slant range calculations, and coverage optimization for various orbital configurations.

1 Executive Summary

Satellite coverage analysis is critical for mission design in Earth observation, communications, and navigation applications. This report analyzes coverage characteristics for various orbital configurations and provides design guidelines for constellation optimization.

2 Mathematical Framework

Definition 1 (Coverage Half-Angle) *The Earth-central angle from the sub-satellite point to the coverage edge:*

$$\rho = \arccos\left(\frac{R_E}{R_E + h}\cos\varepsilon_{min}\right) - \varepsilon_{min} \tag{1}$$

where ε_{min} is the minimum elevation angle and h is orbital altitude.

2.1 Coverage Area

The instantaneous coverage area on Earth's surface:

$$A_{cov} = 2\pi R_E^2(1 - \cos\rho) \tag{2}$$

2.2 Slant Range

The distance from satellite to ground target:

$$d = R_E \left[\sqrt{\left(\frac{R_E + h}{R_E} \right)^2 - \cos^2 \varepsilon} - \sin \varepsilon \right] \tag{3}$$

2.3 Revisit Time

Theorem 1 (Single Satellite Revisit) *For a circular orbit, the maximum revisit time at latitude ϕ:*

$$T_{revisit} \approx \frac{2\pi R_E \cos \phi}{W \cdot n_{orbits/day}} \tag{4}$$

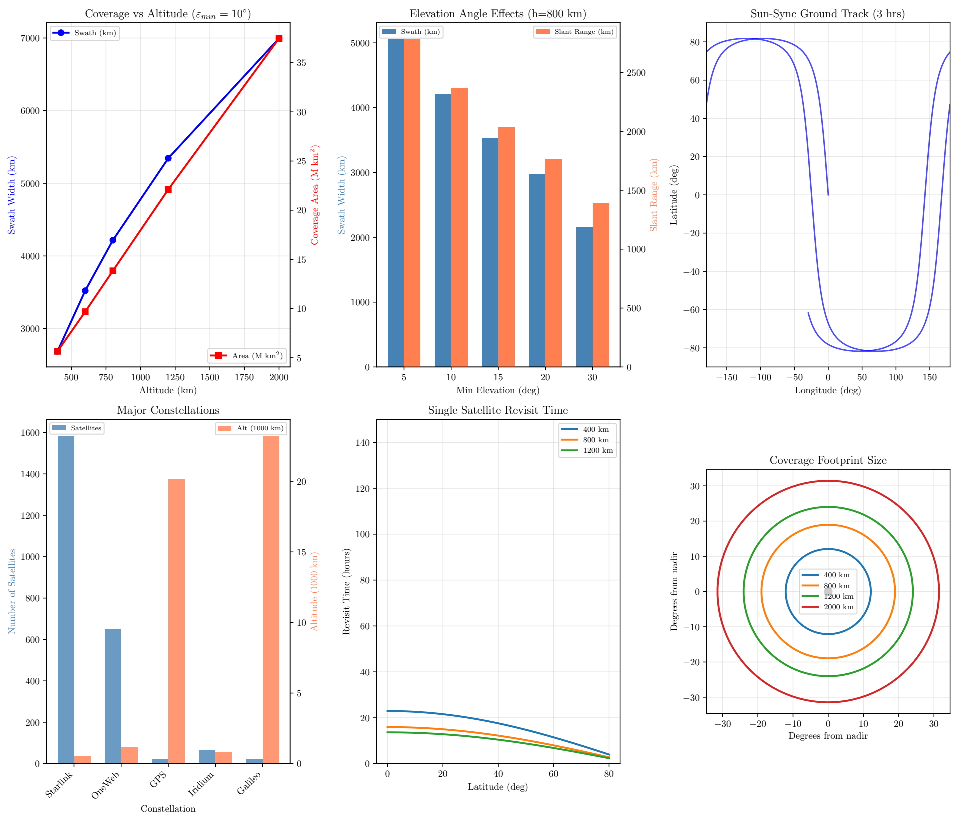
where W is the swath width and $n_{orbits/day}$ is the number of orbits per day.

2.4 Walker Constellation

A Walker Delta pattern is described by notation $i : T/P/F$:

- i = Inclination
- T = Total number of satellites
- P = Number of equally-spaced orbital planes
- F = Relative phasing factor

3 Computational Analysis



4 Algorithm

Input: Orbital altitude h, minimum elevation ε_{min}
Output: Coverage parameters: ρ, A_{cov}, swath width, slant range
$\sin\lambda_0 \leftarrow \frac{R_E}{R_E+h}\cos\varepsilon_{min}$;
$\rho \leftarrow \pi/2 - \varepsilon_{min} - \arcsin(\sin\lambda_0)$;
$A_{cov} \leftarrow 2\pi R_E^2(1-\cos\rho)$;
$W \leftarrow 2R_E\rho$;
$d \leftarrow R_E\sin\rho/\cos(\varepsilon_{min}+\rho)$;
return ρ, A_{cov}, W, d

Algorithm 1: Satellite Coverage Calculation

5 Results and Discussion

5.1 Altitude Trade-offs

For the reference altitude of 800 km:

Table 1: Coverage Parameters vs Altitude ($\varepsilon_{min} = 10°$)

Altitude (km)	Period (min)	Swath (km)	Coverage (M km^2)	Slant (km)	Orbits/ day
400	92.4	2687	5.65	1439	15.6
600	96.5	3522	9.68	1932	14.9
800	100.7	4217	13.84	2366	14.3
1200	109.3	5345	22.11	3131	13.2
2000	127.0	6994	37.47	4435	11.3

- Coverage half-angle: 19.0°
- Swath width: 4217 km
- Instantaneous coverage: 13.84 million km^2
- Orbital period: 100.7 minutes
- Orbits per day: 14.3

Remark 1 (Altitude Selection Trade-offs) *Higher altitudes provide larger coverage footprints but at the cost of:*

- *Increased slant range (reduced resolution)*
- *Higher launch cost*
- *Longer signal delay (latency)*

LEO constellations like Starlink use lower altitudes (550 km) for low latency, while GPS uses MEO (20,180 km) for fewer satellites to achieve global coverage.

5.2 Elevation Angle Effects

Table 2: Effect of Minimum Elevation Angle (h=800 km)

ε_{min} (deg)	Swath (km)	Slant Range (km)	Coverage (M km^2)
5	5057	2783	19.83
10	4217	2366	13.84
15	3533	2032	9.74
20	2980	1768	6.94
30	2157	1395	3.65

Remark 2 (Elevation Angle Selection) *Lower elevation angles increase coverage but degrade link quality due to:*

- *Longer atmospheric path (attenuation, scintillation)*
- *Higher multipath interference*
- *Increased geometric dilution of precision (GDOP) for navigation*

Typical values: 5-10° for communications, 10-15° for navigation, 20-30° for high-precision applications.

5.3 Constellation Design

Table 3: Major Constellation Configurations

Constellation	Satellites	Planes	Altitude (km)	Inclination
Starlink (Shell 1)	1584	72	550	53.0°
OneWeb	648	18	1200	87.9°
GPS	24	6	20180	55.0°
Iridium	66	6	780	86.4°
Galileo	24	3	23222	56.0°

6 Design Guidelines

6.1 Mission-Specific Recommendations

- **Earth Observation**: Sun-synchronous LEO (600-800 km), consistent lighting
- **Communications (Global)**: MEO or large LEO constellations
- **Navigation**: MEO (20,000+ km) for geometric diversity
- **Broadband Internet**: Dense LEO for low latency
- **Polar Coverage**: High-inclination or Molniya orbits

6.2 Constellation Sizing

Minimum satellites for continuous global coverage:

$$N_{min} \approx \frac{4\pi}{\Omega_{sat}} = \frac{2}{1 - \cos\rho} \tag{5}$$

where Ω_{sat} is the solid angle covered by one satellite.

7 Limitations and Extensions

7.1 Model Limitations

1. **Spherical Earth**: Does not account for Earth oblateness
2. **No terrain**: Ignores terrain masking effects
3. **Circular orbits**: Eccentric orbits not considered
4. **Simplified overlap**: Inter-satellite links not modeled

7.2 Possible Extensions

- J2 perturbation for realistic orbit propagation
- Terrain masking with digital elevation models
- Monte Carlo analysis for coverage statistics
- Inter-satellite link topology optimization

8 Conclusion

This analysis demonstrates the key trade-offs in satellite coverage design:

- Higher altitudes increase coverage but reduce resolution
- Lower elevation angles expand coverage but degrade link quality
- Constellation design must balance satellite count against coverage needs
- Modern mega-constellations (Starlink, OneWeb) use hundreds of LEO satellites for continuous global coverage with low latency

References

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