NASA/TM—2020-216589

Space-Based Relay Simulations

Thomas M. Wallett, Denise S. Ponchak, and Charles E. Niederhaus
Glenn Research Center, Cleveland, Ohio

January 2020

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., "quick-release" reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 757-864-6500

- Telephone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Program
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM—2020-216589

Space-Based Relay Simulations

Thomas M. Wallett, Denise S. Ponchak, and Charles E. Niederhaus
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

January 2020

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

Space-Based Relay Simulations

Thomas M. Wallett, Denise S. Ponchak, and Charles E. Niederhaus
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

This report displays field-of-view studies through computer simulation using the Analytical Graphics, Inc., Systems Tool Kit® (STK®). This task analyzes the potential performance for a variety of circular low-Earth-orbit (LEO) satellites and some relative to various user-mission orbits communicating with geosynchronous-Earth-orbit (GEO) satellites. We further investigate relative data volumes taking into account the varying satellite distances with an omnidirectional user antenna.

Introduction

Computer simulations of field-of-view (FOV) studies using the Analytical Graphics, Inc., Systems Tool Kit® (STK®) (Ref. 1) were performed. These simulations assumed a three-geosynchronous-Earth-orbiting (GEO) satellite system with the satellites located at 50° W, 170° W, and 70° E longitudes. Preliminarily, we also assume that the user-mission low-Earth-orbit (LEO) satellite has an omnidirectional coverage antenna and is in a circular orbit. The GEO satellite antennas and LEO user-mission antenna gain-to-noise-temperature (G/T) and equivalent isotropic radiated power (EIRP) are assumed constant over different look angles.

The International Space Station (ISS) (Ref. 2), a LEO model, and seven highly elliptical orbit (HEO) mission satellite models are each simulated in separate scenarios communicating to the GEO satellite models. These seven HEO satellite models are based on the orbits of the Van Allen Probes A and B (Ref. 3), THEMIS (Ref. 4), XMM-Newton (Ref. 5), Geotail (Ref. 6), INTEGRAL (Ref. 7), IBEX (Ref. 8), and Chandra XRO (Ref. 9).

Geometric Field-of-View Access Studies

Simulations of a three-GEO satellite system connecting by line of sight to a user relay satellite are performed. Access times are a function of the user-mission satellite orbit inclination and altitude for a common GEO FOV. The access time is the total time in the entire simulation period when the user-mission satellite is in the FOV of one or more of the GEO satellites. These times need to be accurate to within ±0.1 percent since this affects the simulation fidelity, especially at higher altitudes.

The line-of-sight communication connection between the user-mission satellite and any of the GEO satellites occurs when the mission satellite is in the FOV of the closest GEO satellite. The 1-year simulation time starts on July 1, 2000, at 16:00 UTC and ends on July 1, 2001, at 16:00 UTC. The GEO satellites are grouped together in a constellation. On each of those satellites, a sensor is attached, nadir-facing the Earth, with all sensors simultaneously having conical FOV with half angles of ±7° through ±15°, ±20°, ±25°, and ±30° at a time for each simulation. These sensors are then "chained" together, operating as one unit.

Figure 1 illustrates three GEO satellites each at 35,788.1-km altitude with a generic LEO relay satellite model at 10,000-km altitude and 0° inclination. The altitude of LEO circular orbits vary from 100 to 10,000 km in increments of 100 km with four different inclinations of 0°, 28.5°, 51.6°, and 98°. For all 12 GEO FOV half angles, simulations are performed using the Analytical Graphics, Inc., STK® Analyzer (Ref. 10). The ISS and seven HEO models orbit simulations are performed individually, using their characteristic orbital parameters, for each of the 12 GEO FOV half angles.

For the 1-year simulations, the LEO to GEO satellite model total-access percent durations are found as a function of the LEO inclination angle, GEO FOV, and the LEO altitude. All combinations of each of the 4 values of LEO inclination, 12 values of GEO FOV, and 100 values of LEO altitude are simulated. Since the LEO is circular, the LEO semimajor axis is simply the radius of the circular LEO. This is equal to the average radius of the Earth, given as approximately 6,378.1 km, plus the LEO altitude (Ref. 11). Using results from the STK® Analyzer's chain individual strand access, we find the start, stop, and duration times for each continuous connection in the period. Figure 2 to Figure 5 show both the yearly percentage access and its relativity to a 10° GEO FOV as a function of the LEO altitude for LEO inclination at 0°, 28.5°, 51.6°, and 98°.

The discontinuity in the first derivative of the curves for a 0° inclination LEO satellite in Figure 2 can be explained using Figure 6. The four LEO in Figure 6 are where the discontinuities occur. In Figure 6, it can be seen that 100 percent access occurs up to Orbit 1. From Orbit 1 to Orbit 2, the access decreases.

From Orbit 2 to Orbit 3, the access begins to increase until it decreases again from Orbit 3 to Orbit 4. Past Orbit 4, the access should continue to decrease although this is not shown.

A Microsoft Excel spreadsheet is used to calculate those altitudes for the critical 0° inclination LEO satellite orbits using standard geometrical considerations. The total access duration times for the LEO simulations decrease gradually as the LEO inclination angle increases. This decrease occurs at a higher rate for higher inclination angles. These times also decrease steadily as the LEO altitude increases, except for a limited region of LEO altitudes where the GEO FOV extends beyond the Earth. In general, the total access duration time increases as the GEO FOV values increase, however, due to lack of pole coverage, an anomaly occurs at 98° LEO inclination for 9° GEO FOV at low altitude. One characteristic of the LEO satellite simulations is that the access times for each LEO inclination approach similar corresponding maximum values. This characteristic occurs at GEO FOV values greater than an observed value typically falling somewhere between 9° and 10°. However, under the observed value, the lower the GEO FOV value becomes, the more disparate the access times for the four LEO inclinations become with higher values corresponding to the lower LEO inclinations. As exhibited in Figure 7, the maximum altitude for complete 100 percent access between the LEO satellite and any GEO satellite is nearly linear with most angles of the GEO FOV having the same slope regardless of the LEO inclination.

The inclinations of the other orbit models are ISS (51.6°), Van Allen Probes A and B (10.2°), THEMIS (16.0°), XMM-Newton (67.1338°), Geotail (10.51°), INTEGRAL (54.0°), IBEX (45.8582°), and Chandra XRO (76.7156°). The yearly percentage access versus GEO FOV for them is summarized in Figure 8.

Data Volume Studies

Data volumes can be inferred by simulating a transmitter on the user-mission satellite, which connects and sends data to only the closest of the GEO satellite receivers by using a special feature, CommSystem, available in the Analytical Graphics, Inc,. STK® SatPro version. This feature was specifically designed to model dynamically configured communications links between constellations of transmitters and receivers in order to constrain the access to only the nearest of receivers. Since the user-mission satellite would occasionally access more than one GEO satellite simultaneously, we forced it to link to only one satellite at a time by placing it in its own constellation.

The LEO transmitter power was set to 10 dBW, the transmitter and receiver gains were set to 0 dB, and the transmission frequency was set to 26 GHz in the Ka band, while the data rate was arbitrarily set to a constant 1 bit/s for simulation purposes. Quadrature phase shift keying (QPSK) was used and possible data rates were calculated based on the generated link budget.

The CommSystem link information detailed report lists the bit energy to noise power density (Eb/No) in dB for approximately each minute during connection periods. Since 2.9 dB at 10^{-5} bit error rate (BER) is the approximate minimum Eb/No needed for the data connection to a Tracking and Data Relay Satellite (TDRS), we assumed this value for simulation purposes (Ref. 11). Using this value, we applied the excess Eb/No above 2.9 dB toward the 0 dBHz (1 bit/s) data rate. The value of the data rate was then increased into the kbps range. This shows the maximum data rates, which are available throughout the orbit and simulation.

Throughout the varying distances in the orbit, given a minimum Eb/No connection value, the data volume is calculated by multiplying each time interval in the CommSystem link information detailed report by the corresponding calculated data rate. The total data rate for the 1-year simulation period was then found by the summation of the individual intervals.

The 1-year data volumes (Gb) for 0°, 28.5°, 51.6°, and 98° inclination LEO satellites at 100 to 1,000 km in steps of 100 km altitude are determined as a function of GEO FOV and presented in Figure 9 to Figure 12. The data volumes (Gb) for the ISS LEO and the seven various HEO satellite orbit models, together, are summarized in Figure 13. The five lowest throughput HEO satellite orbit models data are shown more clearly in Figure 14.

Concluding Remarks

This study serves as a guide to estimate the access and maximum data transfer possible to a geosynchronous-Earth-orbit (GEO) constellation of three satellites from a relay satellite having a similar orbit to those models previously discussed. Several mission scenarios with varying inclinations and altitudes were analyzed to assist with architecture planning. These analyses are limited to line of sight only and ignore antenna patterns. Data is assumed to be transferred when access is available. Results indicate that higher altitude reduces visibility and therefore data volume, but larger field of view (FOV) gives longer access times. Only generic low-Earth-orbit (LEO) satellites and the orbits of specific missions were modeled. Their orbits provided representative mission scenarios for the analysis.

References

1. Analytical Graphics, Inc.: Empowering Innovation for 30 Years. 2019. https://www.agi.com Accessed Oct. 29, 2019.
2. National Aeronautics and Space Administration: International Space Station. 2019. https://www.nasa.gov/mission_pages/station/main/index.html Accessed Oct. 29, 2019.
3. National Aeronautics and Space Administration: Van Allen Probes. 2017. https://www.nasa.gov/van-allen-probes Accessed Oct. 29, 2019.
4. National Aeronautics and Space Administration: THEMIS and ARTEMIS. 2017. https://www.nasa.gov/mission_pages/themis/mission/index.html Accessed Oct. 29, 2019.
5. European Space Agency: XMM-Newton. 2019. https://www.cosmos.esa.int/web/xmm-newton Accessed Oct. 31, 2019.
6. National Aeronautics and Space Administration: Geotail. 2014. https://www.nasa.gov/directorates/heo/scan/services/missions/earth/Geotail.html Accessed Oct. 29, 2019.
7. National Aeronautics and Space Administration: INTEGRAL U.S. Guest Observer Facility. 2014. https://heasarc.gsfc.nasa.gov/docs/integral/inthp_about.html Accessed Oct. 29, 2019.
8. National Aeronautics and Space Administration: IBEX. 2019. https://www.nasa.gov/mission_pages/ibex/index.html Accessed Oct. 29, 2019.
9. National Aeronautics and Space Administration: Chandra X-Ray Observatory (Chandra XRO). 2017. https://www.nasa.gov/directorates/heo/scan/services/missions/ universe/ChandraXRO.html Accessed Oct. 29, 2019.
10. Systems Tool Kit: STK Analyzer. 2019. http://help.agi.com/stk/index.htm#analyzer/analyzer.htm Accessed Oct. 29, 2019.
11. National Aeronautics and Space Administration: Space Network Users' Guide (SNUG). 450-SNUG, 452/Space Network Project, Rev. 10, 2012, p. 6–50.

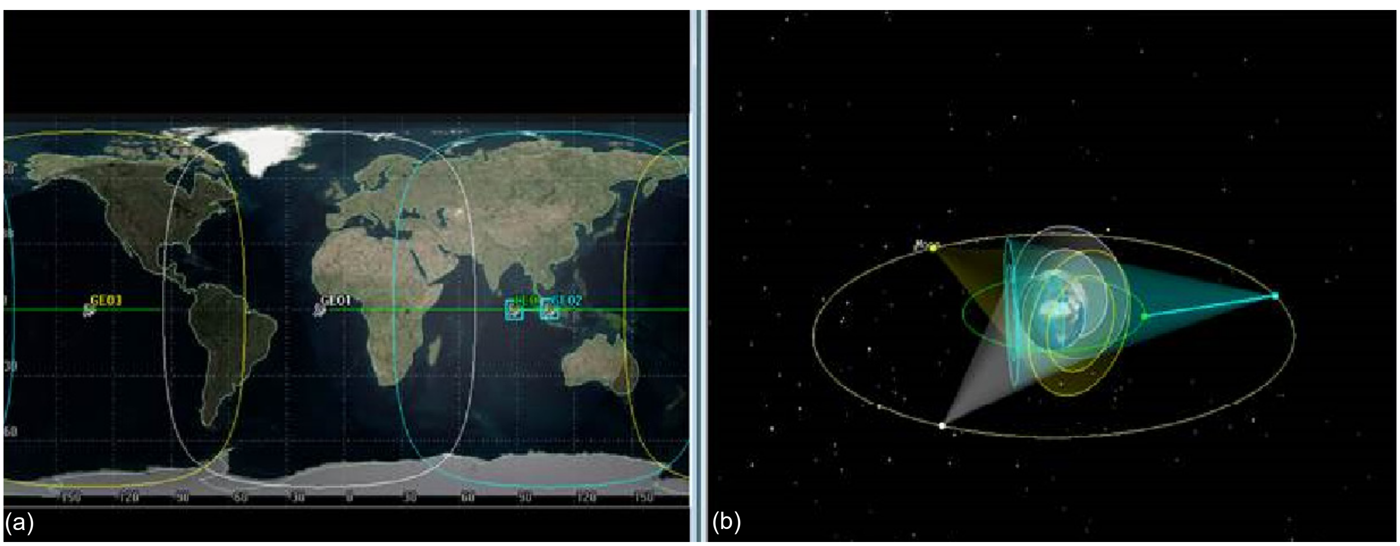


Figure 1.—Views of the low-Earth-orbit (LEO) (0° inclination, 10,000 km altitude) and geosynchronous-Earth-orbit (GEO) satellites. (a) Two dimensional. (b) Three dimensional.

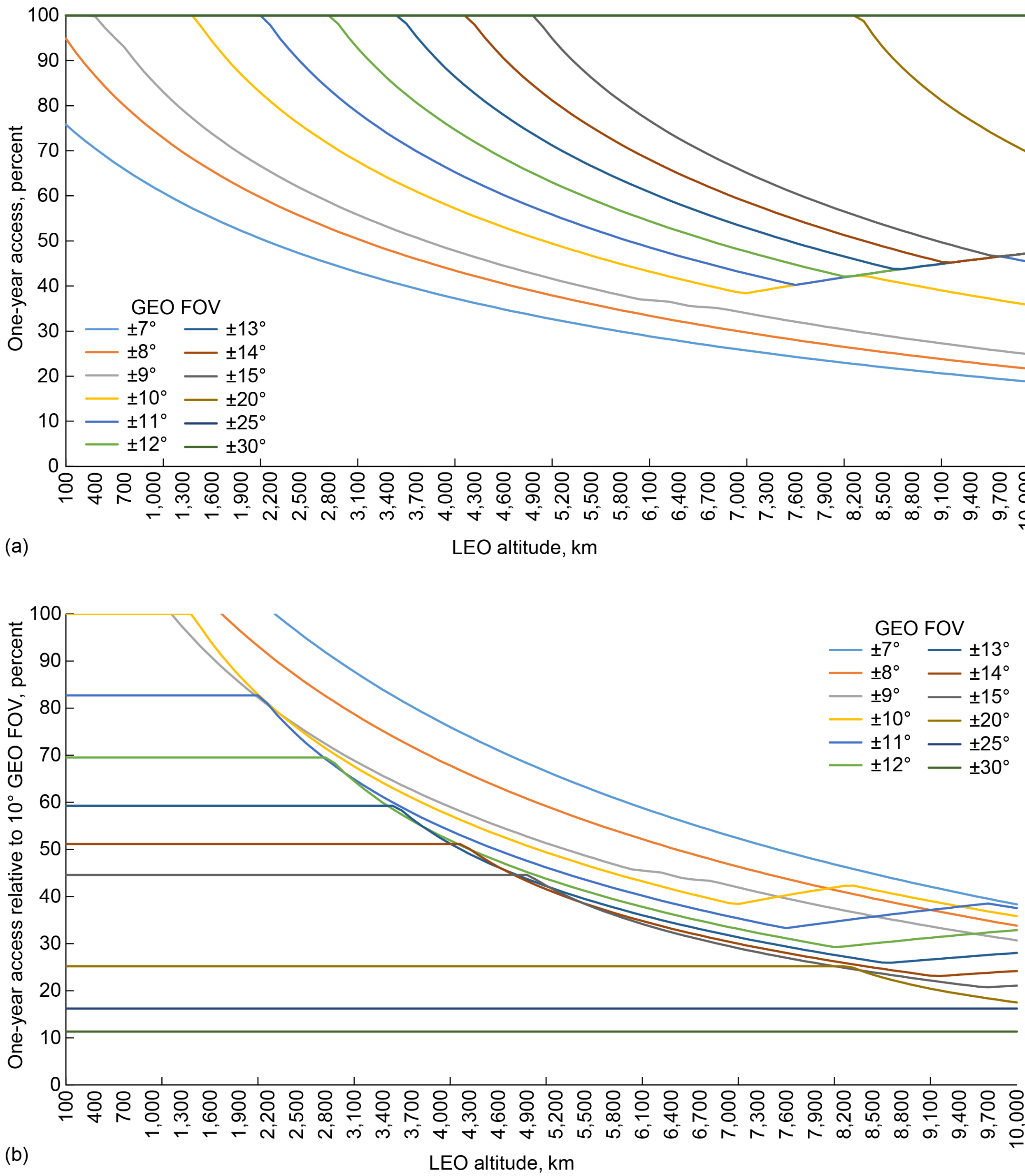


Figure 2.—Types of access versus low-Earth-orbit (LEO) altitude at 0° LEO inclination. Geosynchronous Earth orbit (GEO). Field of view (FOV). (a) One-year access. (b) One-year access relative to 10° GEO FOV.

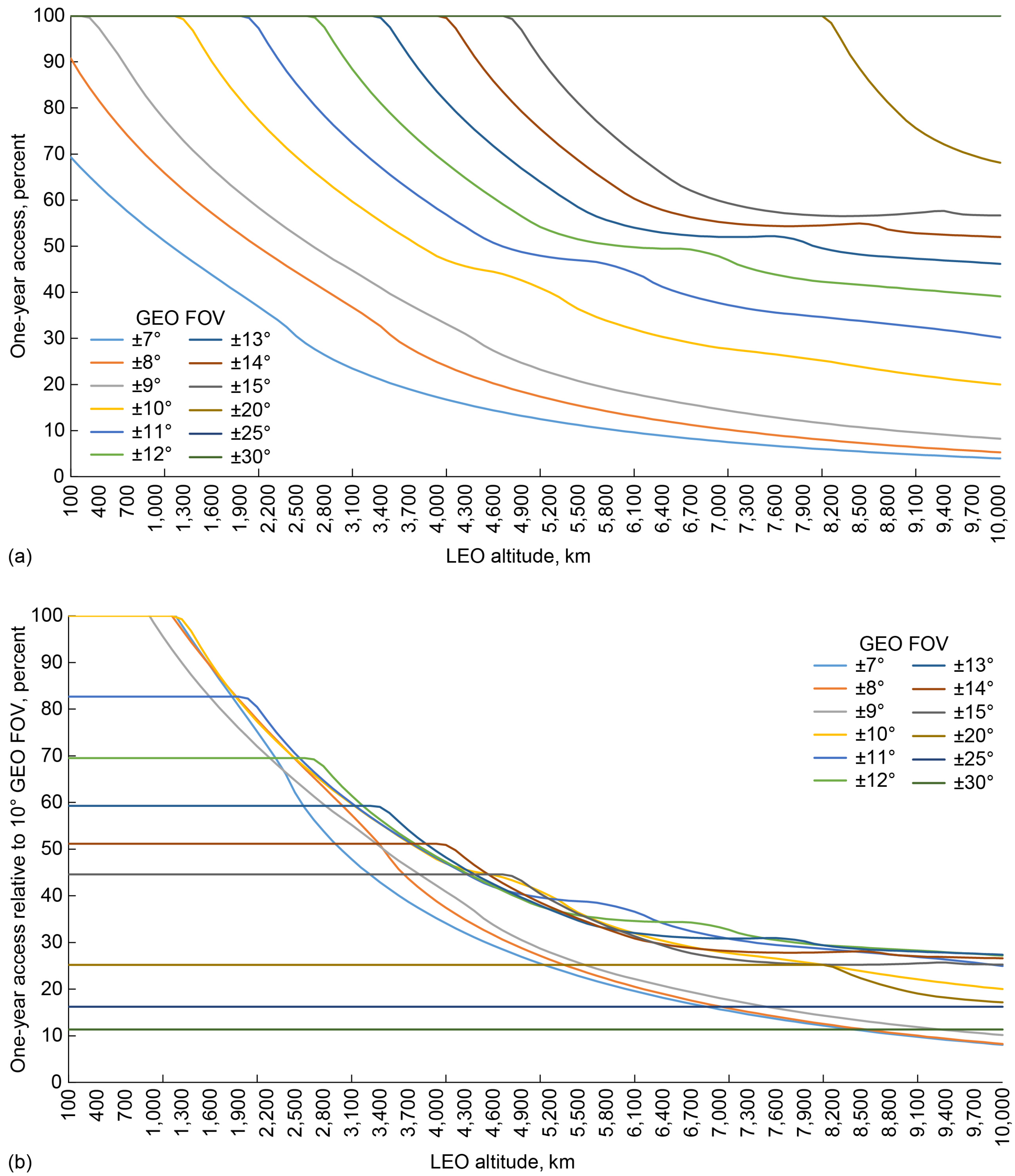


Figure 3.—Types of access versus low-Earth-orbit (LEO) altitude at 28.5° LEO inclination. Geosynchronous Earth orbit (GEO). Field of view (FOV). (a) One-year access. (b) One-year access relative to 10° GEO FOV.

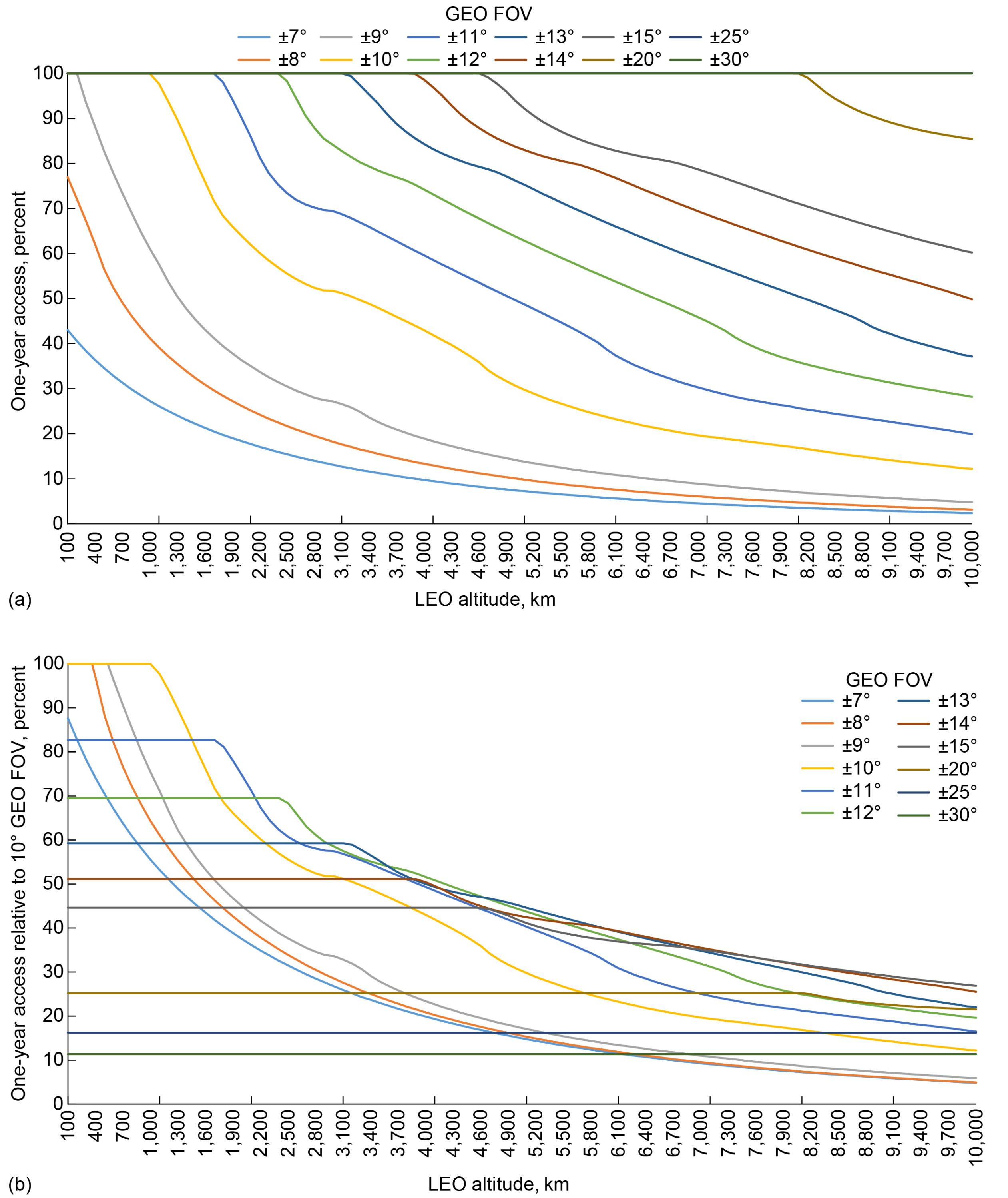


Figure 4.—Types of access versus low-Earth-orbit (LEO) altitude at 51.6° LEO inclination. Geosynchronous Earth orbit (GEO). Field of view (FOV). (a) One-year access. (b) One-year access relative to 10° GEO FOV.

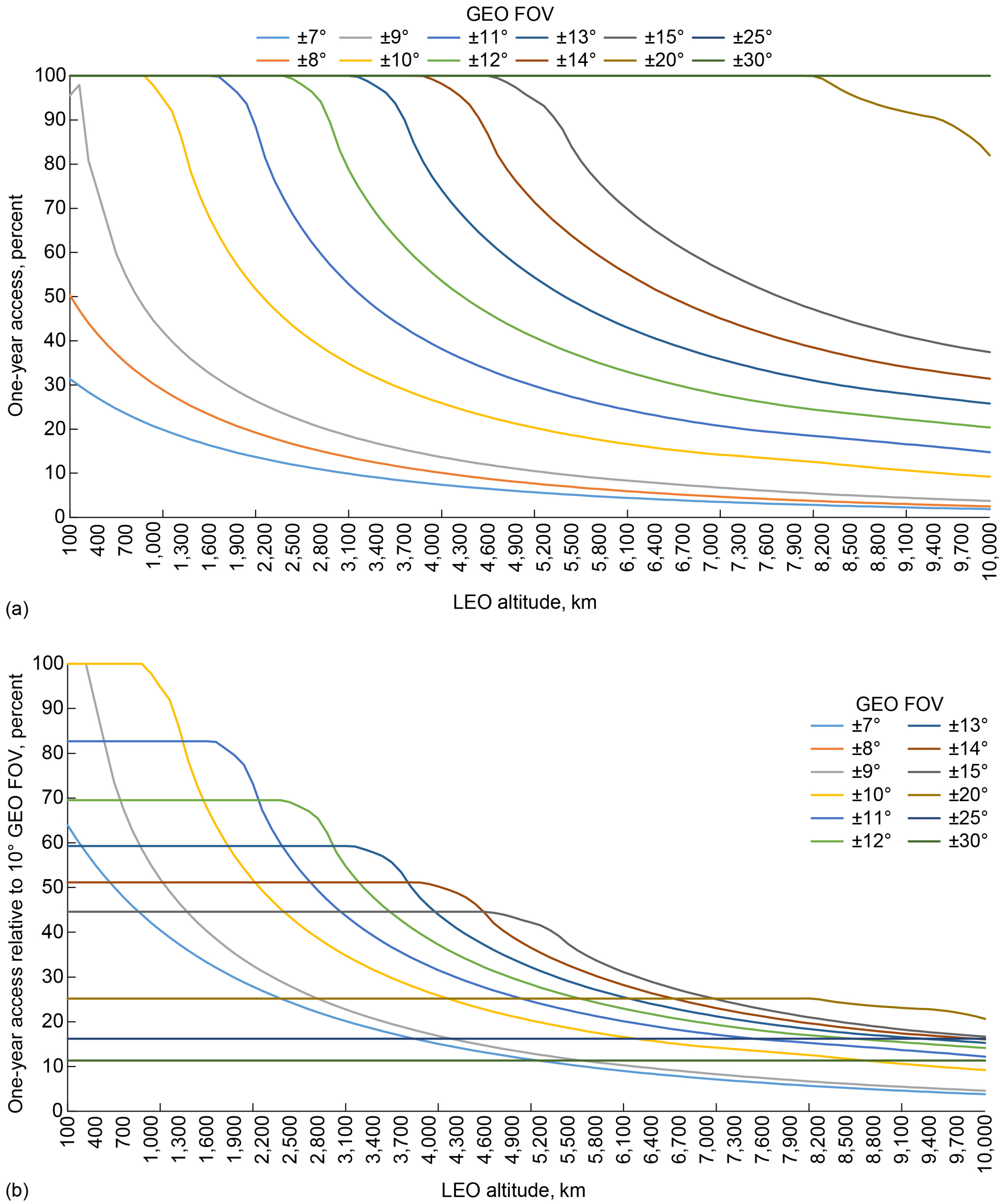
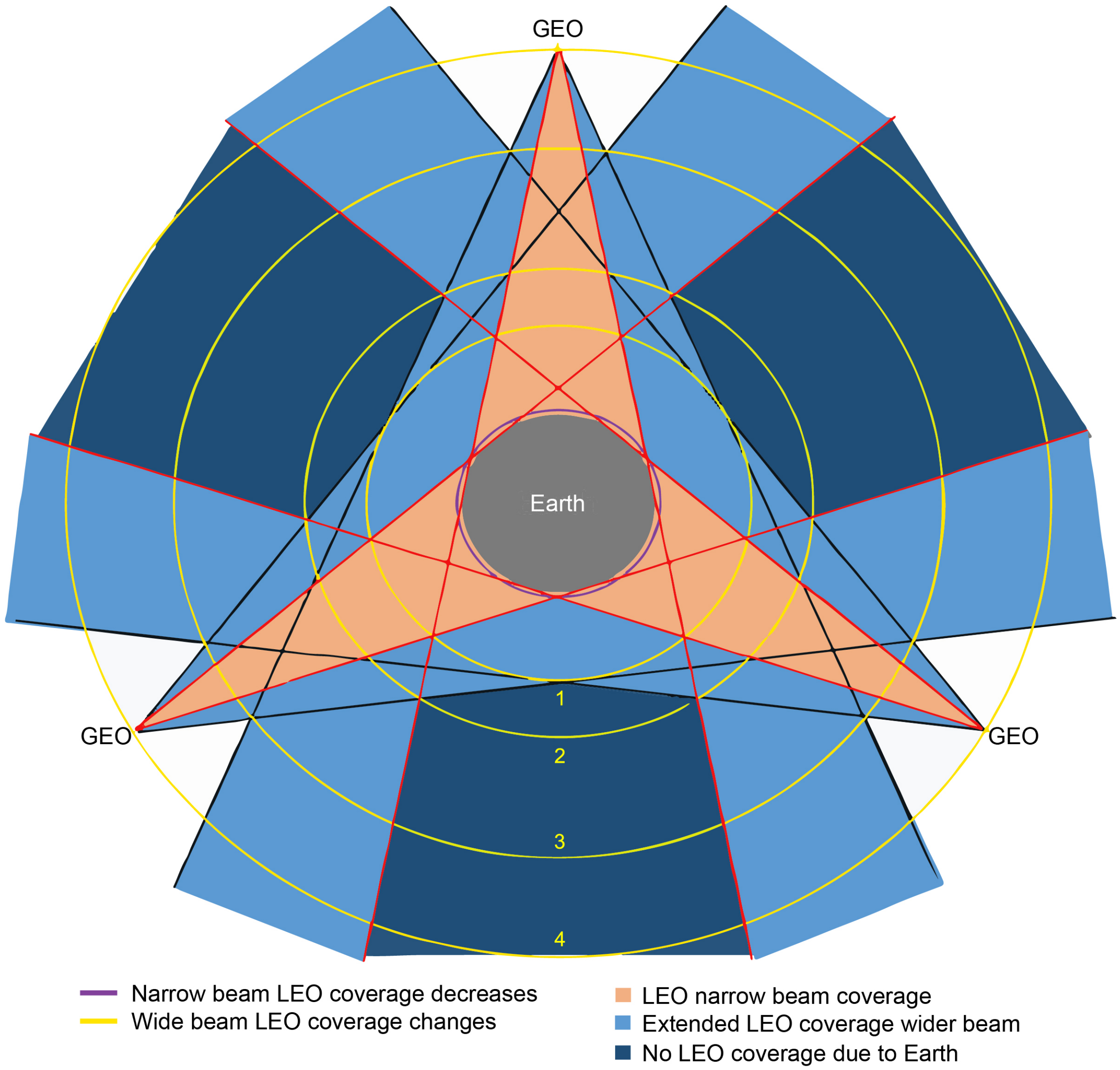


Figure 5.—Types of access versus low-Earth-orbit (LEO) altitude at 98° LEO inclination. Geosynchronous Earth orbit (GEO). Field of view (FOV). (a) One-year access. (b) One-year access relative to 10° GEO FOV.



GEO FOV half-angle, deg/Earth radius, km	10	6378.137
LEO altitude, km/LEO radius, km	1000	7378.137
GEO altitude, km/GEO radius, km	35786.033	42164.170
GEO minimum 100 percent access half-angle, deg/shadow, deg	8.066	8.700
LEO altitude (orbit 1), km/radius, km	1413.487	7791.624
LEO altitude (orbit 2), km/radius, km	7069.859	13447.996
LEO altitude (orbit 3), km/radius, km	8265.325	14643.462
LEO altitude (orbit 4), km/radius, km	35786.033	42164.170

Figure 6.—Two-dimensional representation of three satellites in geosynchronous Earth orbit (GEO) each with a narrow and wide field-of-view (FOV) and satellite orbits at 0° inclination, which are in circular low-Earth orbit (LEO).

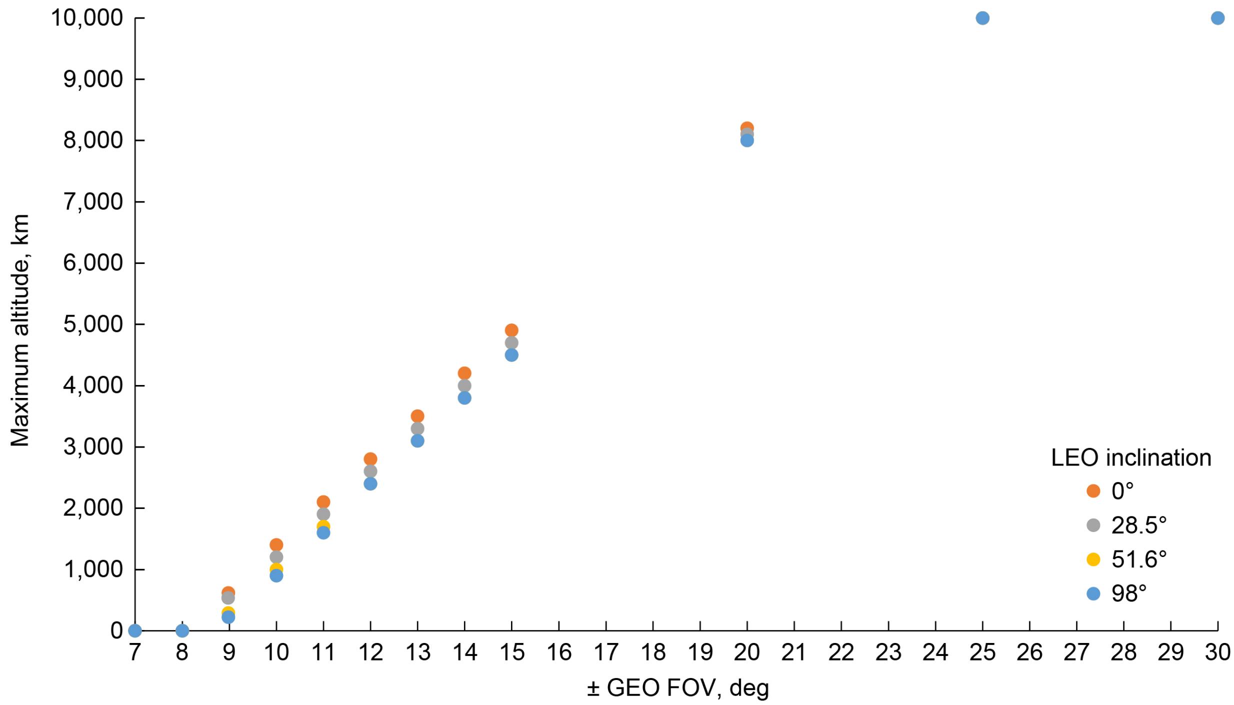


Figure 7.—Maximum altitude for 100 percent access between the low-Earth-orbit (LEO) and any geosynchronous-Earth-orbit (GEO) satellites for a 2-week timeframe. Minimum 800 km for 98° LEO inclination.

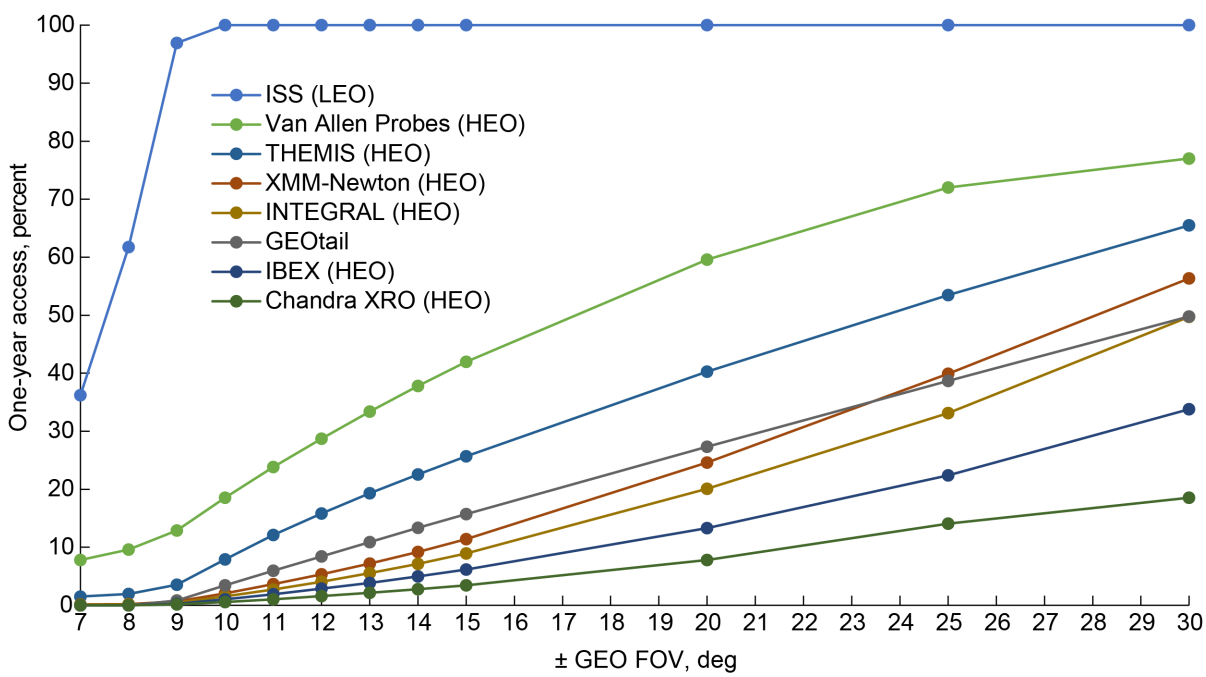


Figure 8.—One-year access versus geosynchronous-Earth-orbit (GEO) field of view (FOV) for International Space Station (ISS) in low-Earth orbit (LEO) and seven satellites in highly ellipitical orbit (HEO).

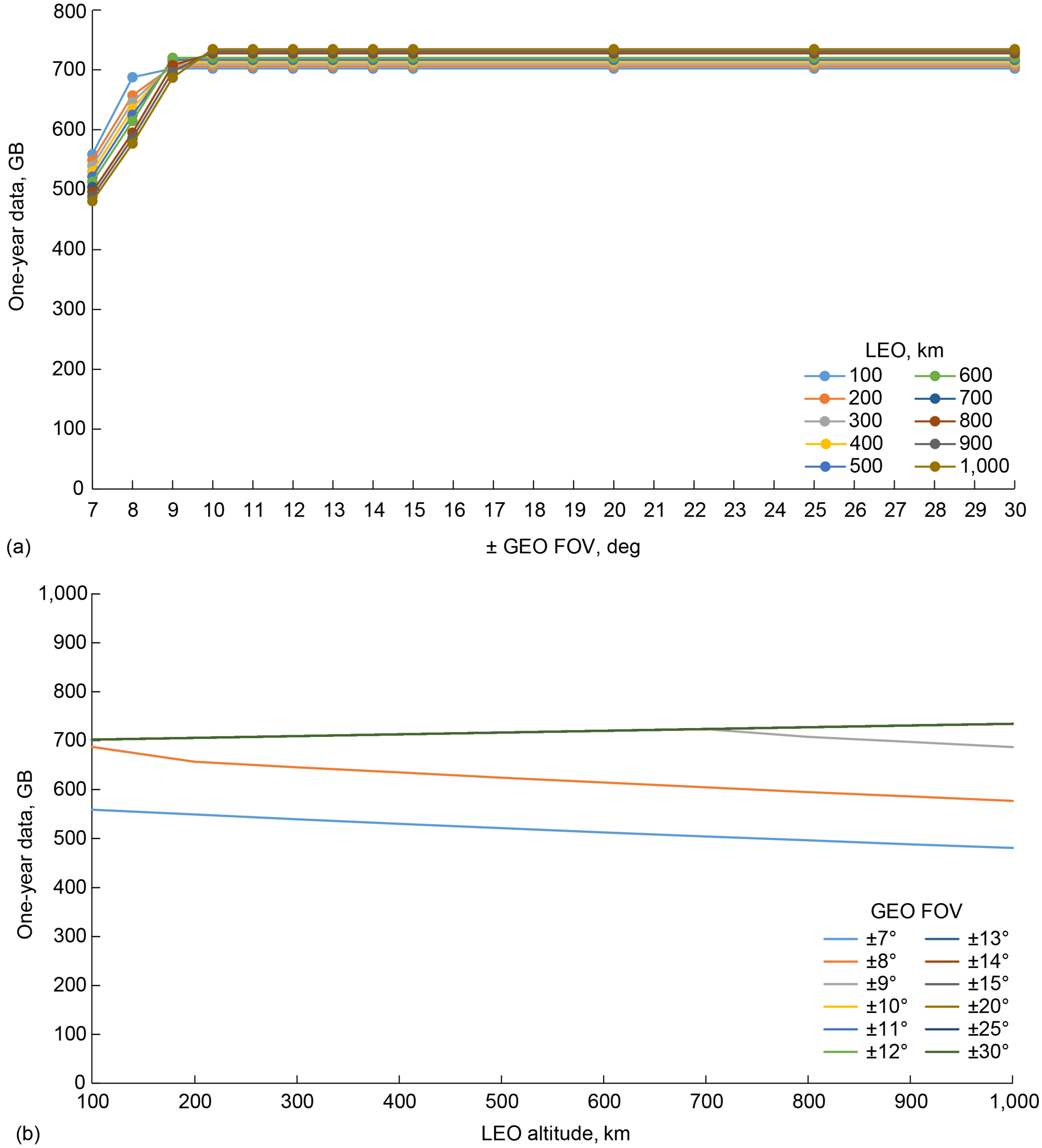
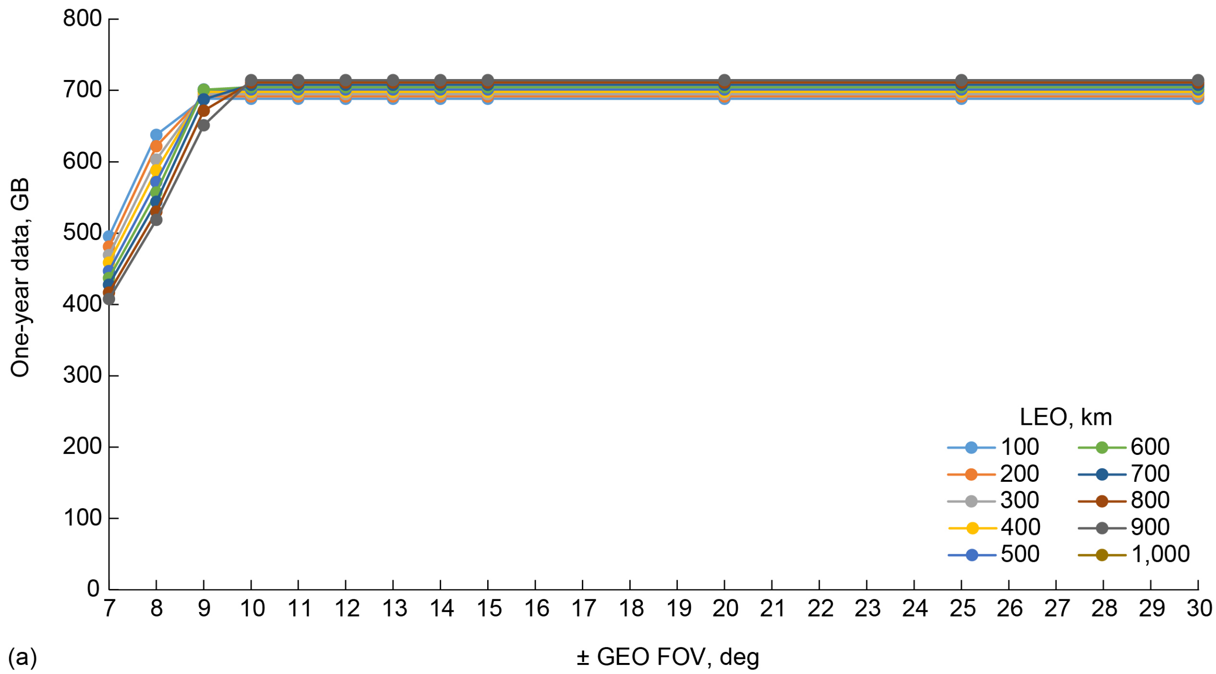


Figure 9.—One-year data for 100 to 1,000 km low-Earth-orbit (LEO) satellites at 0° LEO inclination. Geosynchronous Earth orbit (GEO). Field of view (FOV). (a) GEO FOV angle. (b) LEO altitude.



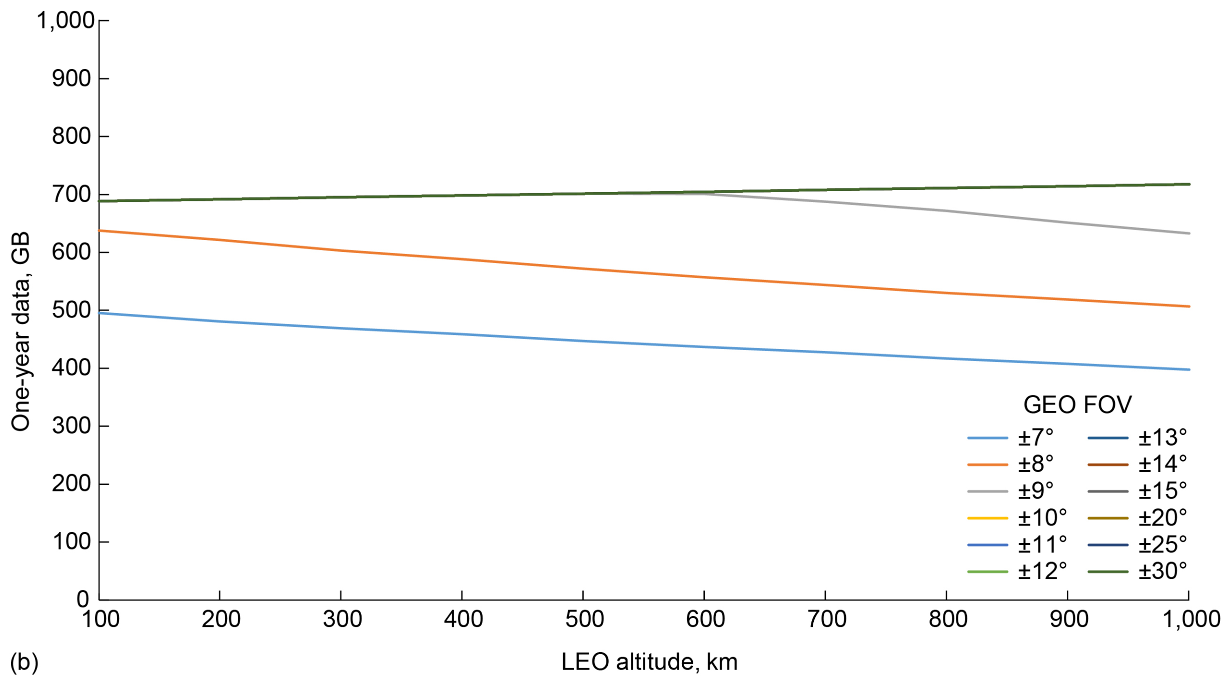


Figure 10.—One-year data for 100 to 1,000 km low-Earth-orbit (LEO) satellites at 28.5° LEO inclination. Geosynchronous Earth orbit (GEO). Field of view (FOV). (a) GEO FOV angle. (b) LEO altitude.

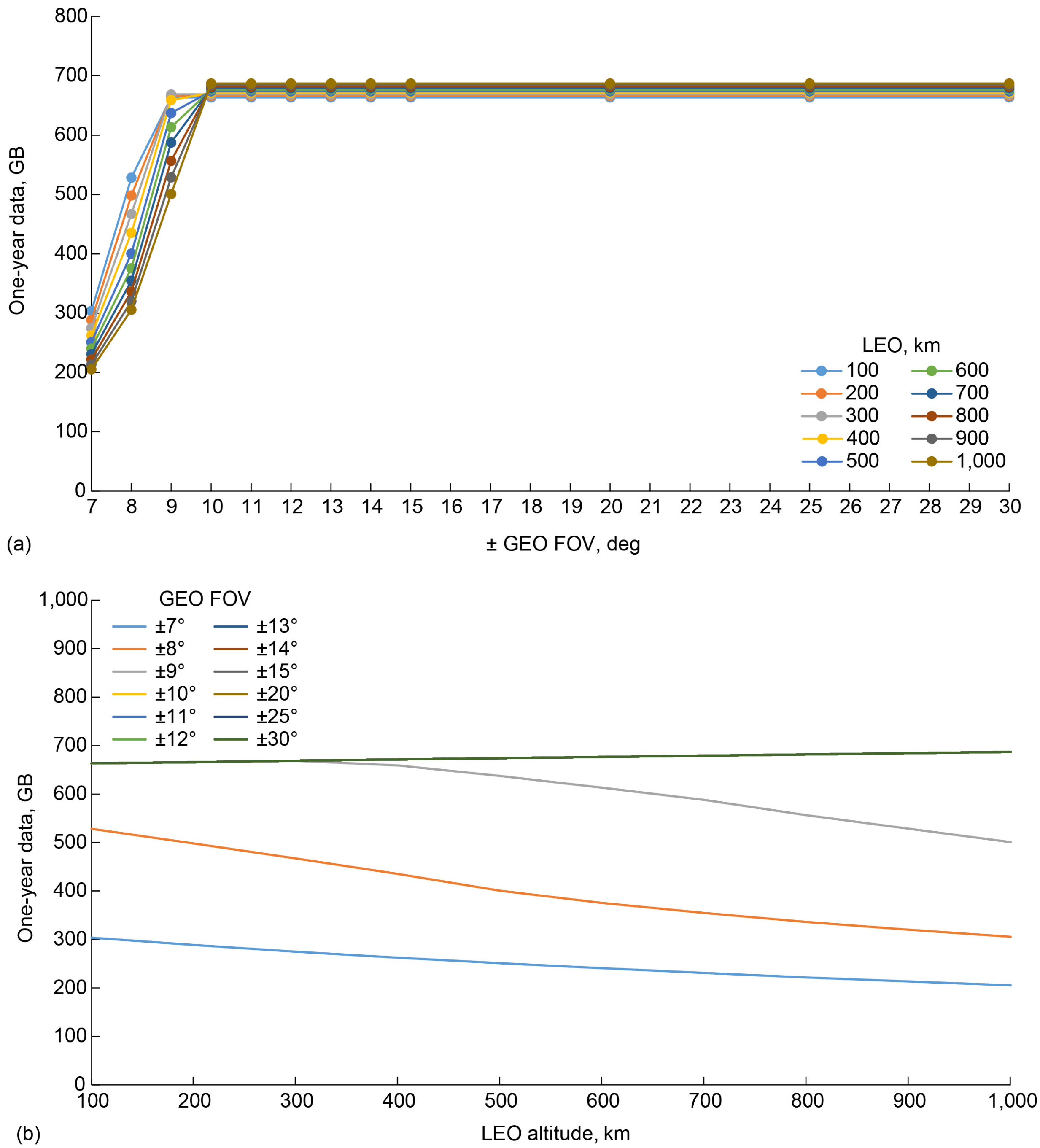


Figure 11.—One-year data for 100 to 1,000 km low-Earth-orbit (LEO) satellites at 51.6° LEO inclination. Geosynchronous Earth orbit (GEO). Field of view (FOV). (a) GEO FOV angle. (b) LEO altitude.

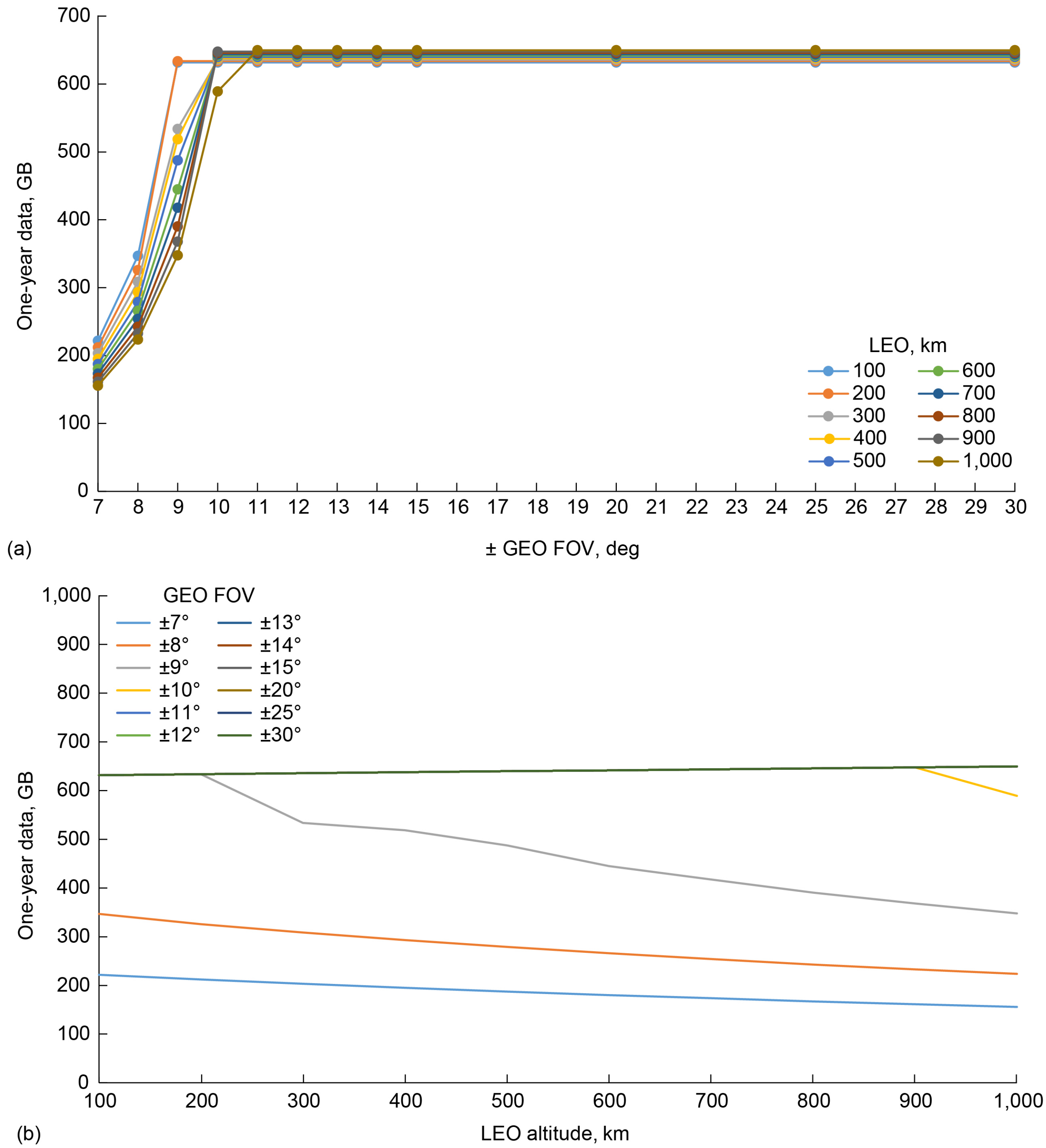


Figure 12.—One-year data for 100 to 1,000 km low-Earth-orbit (LEO) satellites at 98° LEO inclination. Geosynchronous Earth orbit (GEO). Field of view (FOV). (a) GEO FOV angle. (b) LEO altitude.

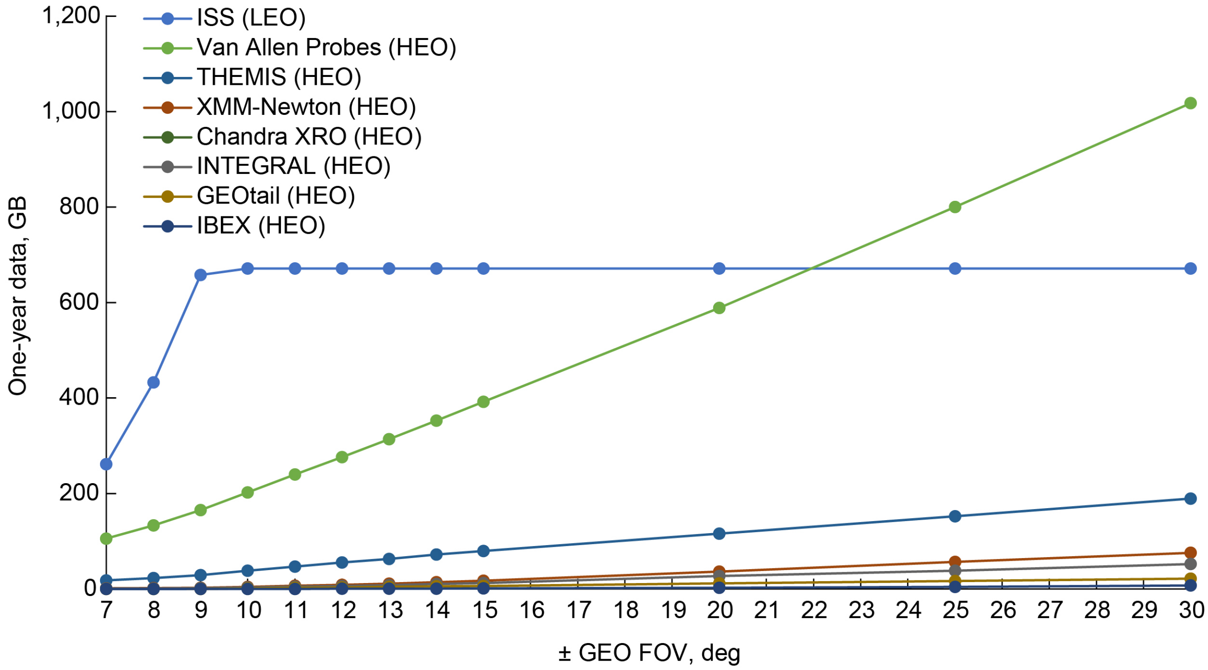


Figure 13.—One-year data versus geosynchronous-Earth-orbit (GEO) field of view (FOV) for the International Space Station (ISS) model in low-Earth orbit (LEO) and seven highly elliptical orbit (HEO) satellite models.

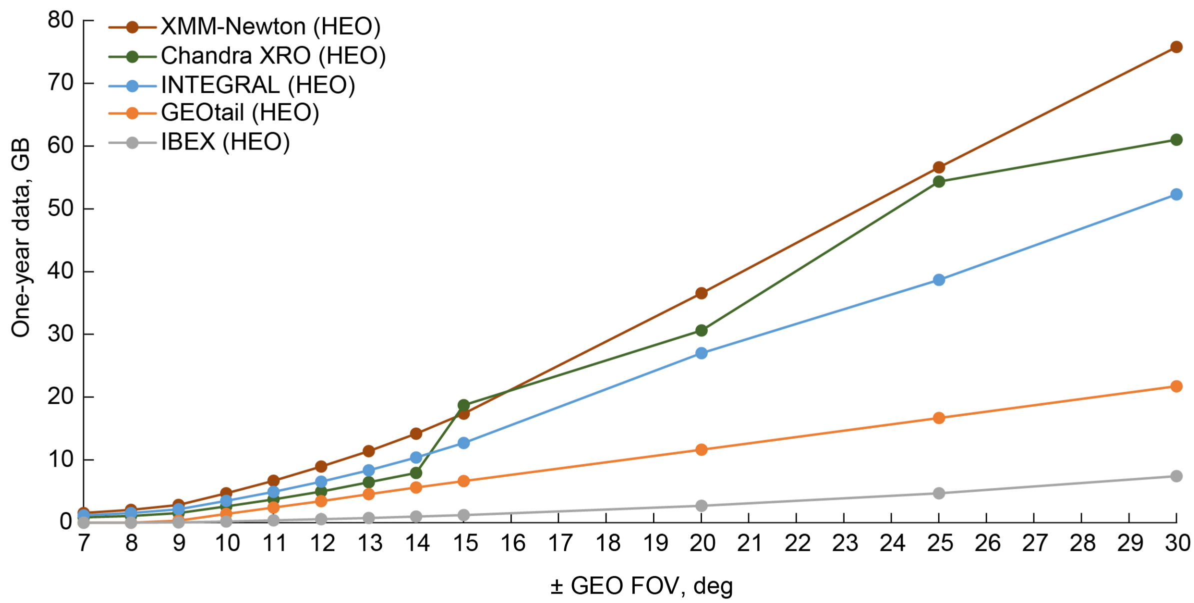


Figure 14.—One-year data versus geosynchronous-Earth-orbit (GEO) field of view (FOV) for the five lowest throughtput highly elliptical orbit (HEO) satellite models.