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Revisiting the Earth's Spectral Radiance Shell Concept for a Constellation of Small Environmental Satellites

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INTRODUCTION

Remote sounding of the atmosphere, radiation budget studies, satellite observation of surface properties, and many other atmospheric measurements require knowledge of the radiation leaving Earth. Ideally, we would like to know the radiance as a function of time, latitude, longitude, height, direction, and wavelength. One can think of a shell surrounding Earth on which we wish to know the spectral radiance leaving Earth. We call this shell the spectral radiance shell, and we first introduced the idea in 2004 (*1*).

It must be noted that the spectral radiance shell concept is an idealized one, much like a blackbody. No set of instruments can completely measure the spectral radiance shell parameters, just as no perfect blackbody can be constructed. Yet each can be used as a standard to gauge the value of what can be achieved. Here we focus on observations made by Low Earth Orbiting, nadir-scanning instruments, but limb-scanning and radio occultation instruments can also be studied with the spectral radiance shell concept.

Obviously, spectral radiance shell observations require a constellation of satellites, not one or a few. The good news is that smallsats offer a solution to this problem both because they are less expensive to build and because many smallsats can be launched with a single rocket, thus reducing launch costs. This poster describes the process for designing a smallsat constellation which could make hourly (or more frequent) observations everywhere on Earth and presents several example constellations.

CONSTELLATION DESIGN STEPS

1. Choose a height for the circular orbit.
   - Avoid low orbits (400 km or less) due to atmospheric drag
   - Avoid heights above 1000 km due to Van Allen Belt radiation, which requires hardening of the spacecraft and, thus, extra weight and expense.
   - Avoid heights below about 600 km due to other constellations, like Starlink (*2*).
2. Calculate the swath width of the instrument, based on the height and the maximum scan angle (α), or maximum viewing zenith angle (ζ). (See figure below.)

   $$\sin(\zeta) = \sin(\alpha)\,(r_e + h) / r_e$$

   $$w = 2\,(\zeta - \alpha)$$

3. Choose an inclination angle *(i)* such that the poles are within the swath, that is,

   $$90° - w/2 < i < 90° + w/2$$

   Note that sunsynchronous inclinations are within this range, but the constellation does not require sunsynchronous inclination. Calculate the equator crossing angle:

   $$i' = -\mathrm{ATAN2}\,[\,(2\pi / P)\cos(i) - d\Omega_e/dt,\ -(2\pi / P)\sin(i)\,]$$

   where P is the satellite's nodal period, and $d\Omega_e/dt$ is Earth's rotation rate. See Kidder and Vonder Haar (*3*) for details.

4. Calculate the effective swath width (w'):

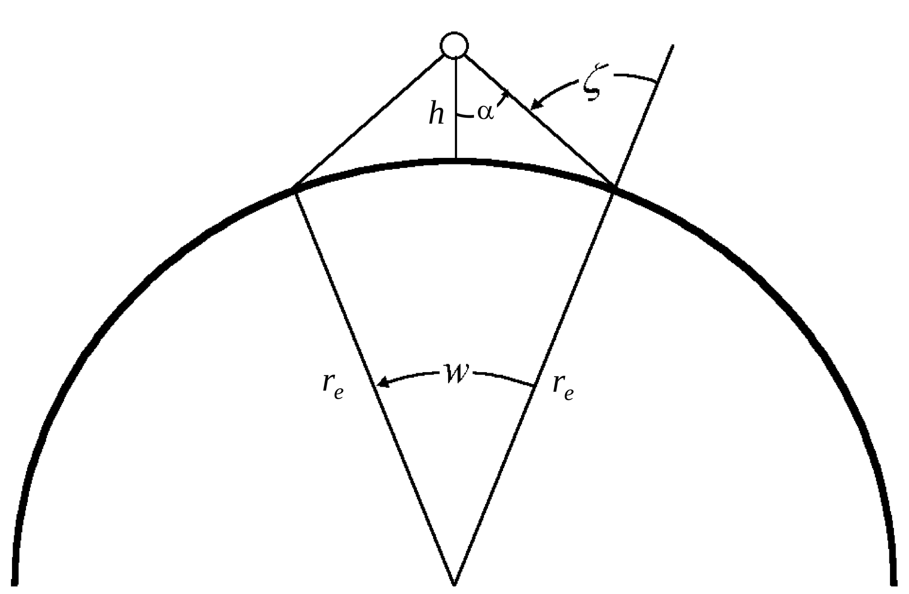
   $$w' = w / \sin(i')$$

5. Calculate the number of planes needed for "no gap" overage:

   $$N_p = 180° / w'$$

   If not an integral result, round up to the next higher integer.

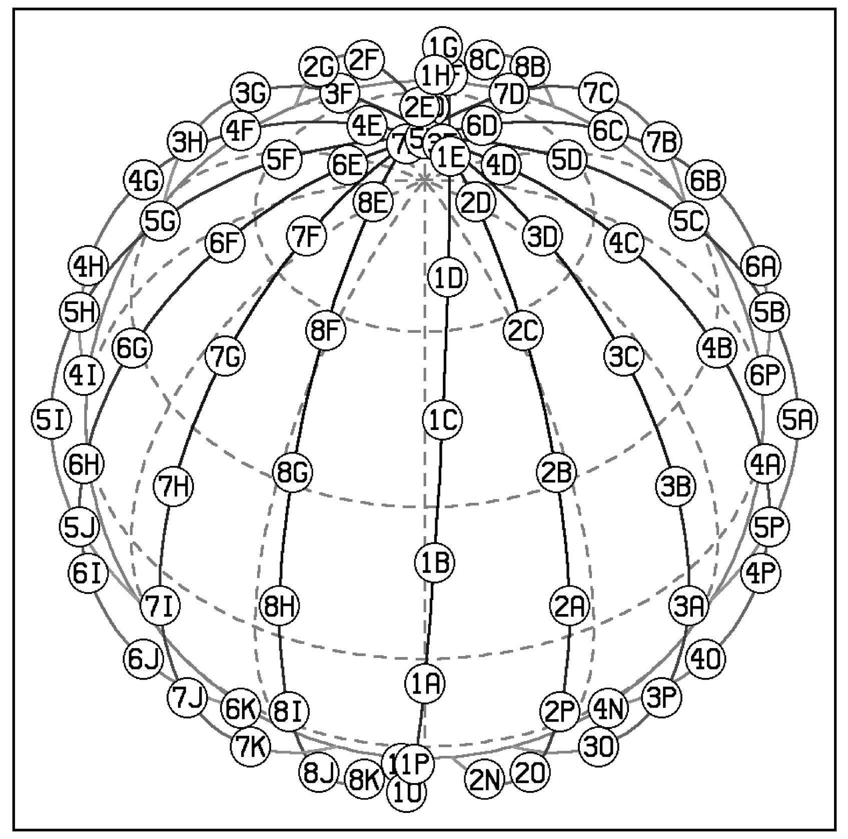
6. Choose the number of satellites per plane (N_{sat}), remembering that the time between of observations (at the equator) is P / N_{sat}. For a "full" constellation, like Iridium (*4*), choose $N_{sat} = 2\,N_p$. For a "sparse" constellation, choose $N_{sat} = 2$, which, at the heights recommended, will result in observation spacing less than 1 hour.



Sketch of the relationship between maximum viewing zenith angle (ζ), maximum scan angle (α), satellite height (h), and swath width (w).

EXAMPLE SPECTRAL RADIANCE SHELL CONSTELLATIONS

Full 650



Choosing a height of 650 km, an inclination angle of 86.1° (equator crossing angle = 90°), and a maximum viewing zenith angle of 70° results in an 8-plane constellation. With 16 satellites per plane (the "full" constellation), there would be 6.12 minutes between observations. This would require 8 launches (with 16 satellites each, for a total of 128 satellites) and would require an instrument which could scan ±58.5° from nadir.

In the figures the satellites are named as follows: the number is the plane number, the letter is the satellite within each plane. In this example, the 16 satellites in each plane are lettered A through P.

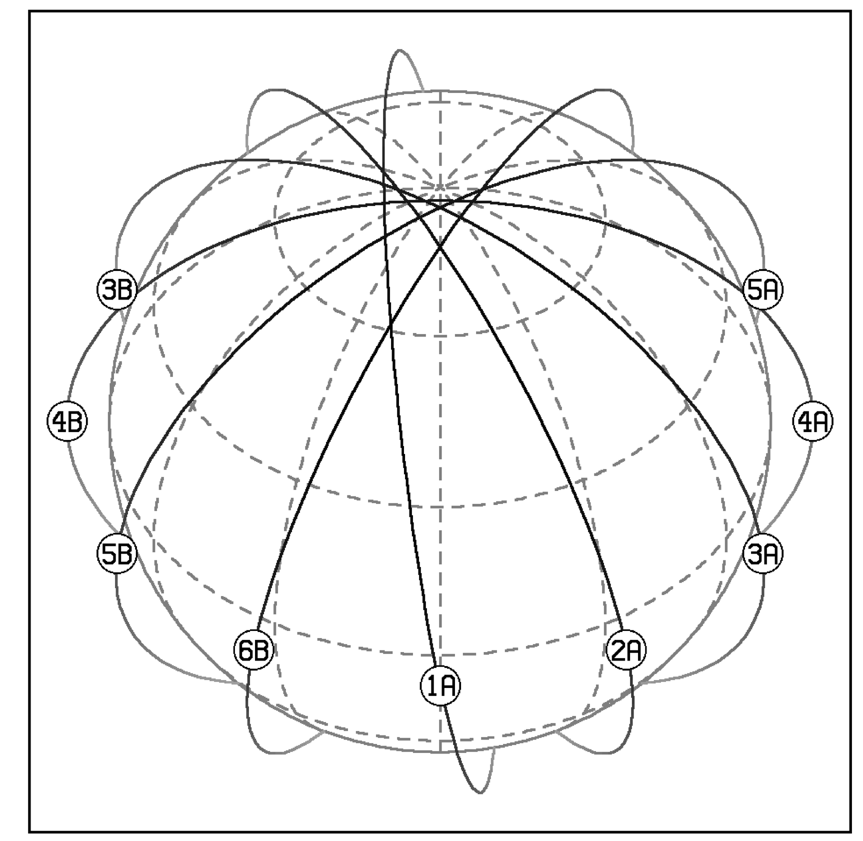
With this design, all of the satellites in one hemisphere are traveling north, and in the opposite hemisphere, south. The line between Plane 1 and Plane 8 separates the two hemispheres.

Also note that in every other plane, the satellites are "staggered" by one half of the spacing between satellites. For example, at the time pictured at the left, satellites 1A, 3A, 5A, and 7A are at the equator (traveling north). Satellites 2A, 4A, 6A, and 8A are north of the equator by one half the satellite spacing. The Iridium satellites communicate with each other; this staggered design minimizes the distance between satellites.

One problem with this design is that getting the data to the ground in a timely fashion for processing and distribution presents a challenge—unless space-based receiving stations like TDRS (*5*) are employed. Historic ground-based receiving stations are far too few to be useful.

Constellation properties of this and all other example constellations are in the table at the bottom of this column.

Supplemental Sunsynchronous



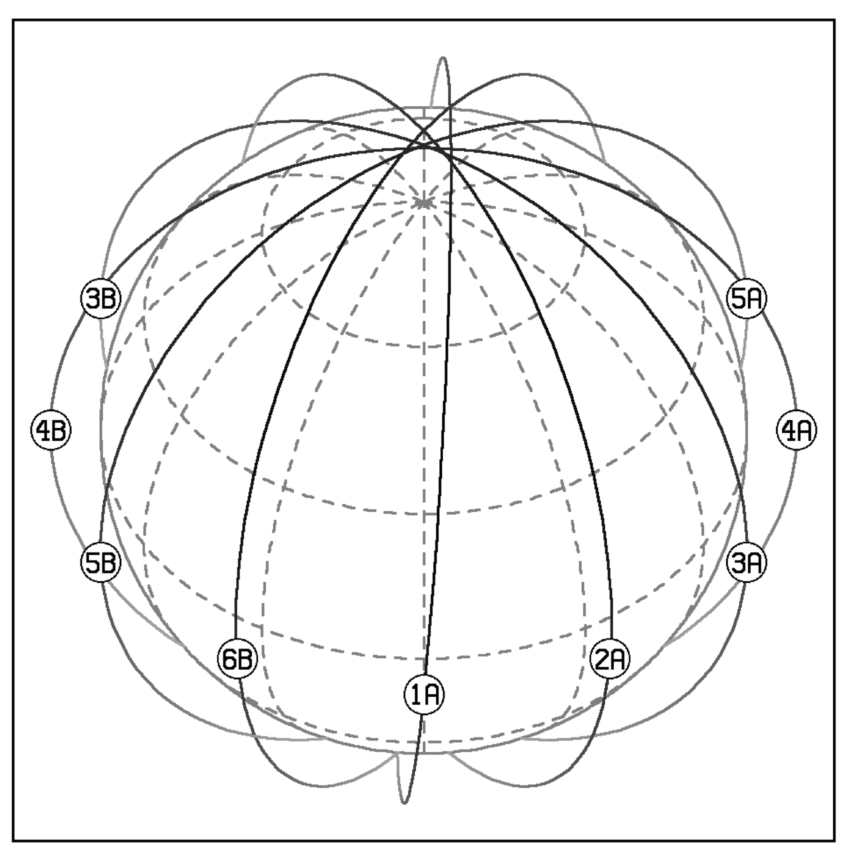
Most meteorological satellites fly in sunsynchronous orbits. The current NOAA satellites (JPSS) fly at 824 km. If we choose a height of 824 km, a sunsynchronous inclination of 98.7°, and 2 satellites per plane—and if we increase the maximum viewing zenith angle to 72.5° and, thus, the maximum scan angle to 57.6°—we get a 6-plane constellation with 50.75 minutes between observations. This would require 6 launches of 2 satellites each.

But, wait! The NOAA (JPSS) satellites already fly in one of these planes (say, Plane 1, at 1330 ascending local time), and the Metop satellites fly in another (Plane 5, at 2130 ascending local time, although at a slightly lower height), which means that two of the six orbital planes are already populated! The Supplemental Sunsynchronous Constellation could be completed with four launches of two satellites each (8 additional smallsats).

The only problem here is that some of the instruments that fly on the NOAA and Metop satellites don't have the required maximum scan angle of 57.6°; therefore, there would be small gaps between adjacent swaths at the equator for data from those instruments.

This is by far the cheapest way to expand the current sunsynchronous constellation to global, hourly observations.

Sparse 1000

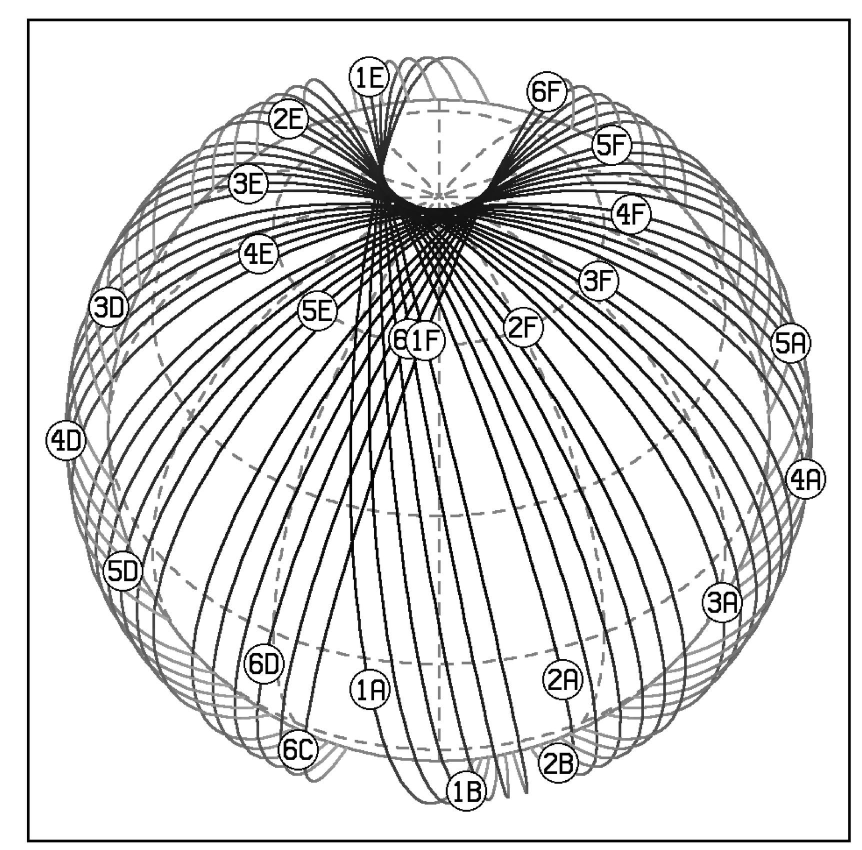


The constellation above has repeat times far shorter than 1 hour, and numbers of satellites far exceeding current constellations. The number of necessary orbital planes decreases with satellite height, and the repeat time decreases with the number of satellites per plane. This example examines the properties of a less voluminous constellation.

Choosing a height of 1000 km, an inclination angle of 85.8° (equator crossing angle = 90°), and a maximum viewing zenith angle of 70° results in a 6-plane constellation. With 2 satellites per plane (the "sparce" constellation), there would be 52.62 minutes between observations. This would require 6 launches (with 2 satellites each, for a total of 12 satelllites) and would require an instrument which could scan ±54.3° from nadir.

Although it costs more to place a satellites in a higher orbit, decreasing the number of launches from 8 to 6 and decreasing the number of satellites by an order of magnitude (from 128 to 12) makes the Sparce 1000 constellation an attractive alternative to the Full 650 constellation. However, there may be limitations on how high smallsats can fly.

Half Formation



So far we've designed constellations with multiple satellites in the same orbital plane. The reason for this is that a single rocket can launch several satellites into one orbital plane. Yes, the satellites need to be spread out in this orbital plane, but that doesn't take too much on-board energy. Changing orbital planes takes more energy. NASA's A-Train satellites (*6*) pioneered formation flying in which satellites fly not in the same orbital plane, but in closely spaced orbital planes such that satellites fly the same ground track; see a simulation here: (*7*).

Plotted at the left is a "half formation", sunsynchronous, 824 km constellation, which is like the constellations discussed previously, but the number of satellites is half of the Full value, i.e., the number of satellites per plane is equal to the number of planes. But there is a small separation (4.25°) between individual planes. (If Δt is the time spacing between adjacent satellites, the angular separation is Δt times the Earth rotation rate relative to the orbital plane.) Do not be fooled: there are no gaps in the observations. All the satellites in one orbital plane fly the same ground track and observe the same swath. Then the next set of satellites fly the same ground track.

If the cost of changing and maintaining orbital planes is not too great, formation flying would be a good thing to try.

Constellation Properties

Constellation	Number of Planes	Plane Spacing (degrees)	Satellites per Plane	Total Satellites	Orbital Altitude (km)	Max viewing Zenith Angle (degrees)	Inclination (degrees)	Nodal Period (minutes)	Time Between Observations (minutes)	Satellites per Launch	Number of Launches	Max Scan Angle (degrees)
Full 650	8	22.5	16	128	650	70.0	86.1	97.9	6.12	16	8	58.5
Sparse 1000	6	30.0	2	12	1000	70.0	85.8	105.2	52.62	2	6	54.3
Supplemental Sunsynchronous	6	30.0	2	12 / 8	824	72.5	98.7	101.5	50.75	2	6 / 4	57.6
Half Formation	6	30.0	6	36	824	72.5	98.7	101.50	16.92	6	6	57.6

References and Notes

1. Kidder, S.Q., and T. H. Vonder Haar, 2004: A Satellite Constellation to Observe the Spectral Radiance Shell of Earth, 13th AMS Conference on Satellite Meteorology and Oceanography, Norfolk, Virginia, 20-23 September 2004, http://cat.cira.colostate.edu/Kidder/SatMet13_P1.1.pdf.
2. "Starlink", *Wikipedia: The Free Encyclopedia*. Wikimedia Foundation, Inc, 22 July 2022, https://en.wikipedia.org/wiki/Starlink.
3. Kidder, S. Q., and T. H. Vonder Haar, 1995: *Satellite Meteorology: An Introduction*. Academic Press, San Diego, 466 pp.
4. "Iridium satellite constellation", ", *Wikipedia: The Free Encyclopedia*. Wikimedia Foundation, Inc, 22 July 2022, https://en.wikipedia.org/wiki/Iridium_satellite_constellation.
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