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A SATELLITE CONSTELLATION TO OBSERVE THE SPECTRAL RADIANCE SHELL OF EARTH

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1. 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 the 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 the earth on which we wish to know the spectral radiance leaving the earth. We call this shell the spectral radiance shell.

Measurements of the spectral radiance shell of earth have been made for many years, but only in a sparse way. Sun-synchronous satellites, for example, view any point near the equator twice per day, but always at the same local times. Satellites such as the Earth Radiation Budget Satellite are not sun-synchronous and sample all local times, but over a period of a month or more. Geostationary satellites make observations at the required temporal resolution, but they do not sample the polar regions, and each point is viewed from only one angle. To improve our knowledge of earth's spectral radiance shell, a new strategy is required.

A satellite constellation is a group of similar satellites (say five or more) that are synchronized to orbit the earth in some optimal way. Satellite constellations have been used for navigation and telecommunication, but not yet for atmospheric observations. The purpose of this paper is to describe a constellation of satellites that could be deployed to observe the spectral radiance shell of earth.

In section 2 the necessary orbital parameters are presented. In section 3 current constellations of satellites are explored. In section 4, a meteorological satellite constellation is constructed. Conclusions are offered in section 5.

2. CONSTELLATION FUNDAMENTALS

Six parameters (called orbital elements) are necessary to characterize a satellite orbit. Three of the parameters, the semi-major axis, the eccentricity, and the mean anomaly, describe where the satellite is in the plane of its elliptical orbit. Most satellite orbits are very nearly circular (eccentricity zero); thus, they move with constant radius (r) and a constant angular velocity around the center of the earth.

The final three orbital elements describe the orientation of the plane of the orbit with respect to the right ascension-declination coordinate system, a Cartesian coordinate system that is essentially fixed with respect to the stars. The center of the coordinate system is at the center of the earth; the z-axis coincides with the earth's spin axis, the *x*-axis points to the vernal equinox (the line between sun and earth at the moment when the sun crosses the equator going north), and the *y*-axis completes a right-handed coordinate system The three parameters, all angles, are the right ascension of ascending node, the argument of perigee, and the inclination angle. These are illustrated in Fig. 1. The perigee is the point where the satellite is closest to the center of the earth. Since we are interested in circular orbits, the argument of perigee will not be needed. The plane of the orbit is determined by the inclination angle (i) and the right ascension of ascending node (Ω).

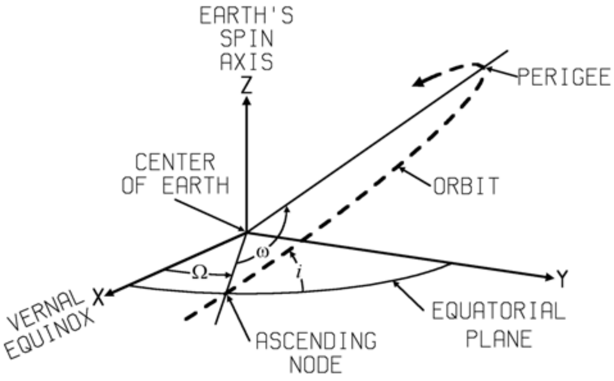

Figure 1. Sketch of three of the orbital elements: Ω = right ascension of ascending node; ω = argument of perigee; i = inclination angle. [After Kidder and Vonder Haar (1995).]

The period of these satellites is given by

$$T = \frac{2\pi}{\sqrt{Gm_e}} r^{3/2} \left[1 - \frac{3}{2} J_2 \left(\frac{r_{ee}}{r} \right)^2 \left(3 - 4\sin^2 i \right) \right], \qquad (1)$$

where $Gm_e = 3.986005 \times 10^{14}$ m^3 s^{-2} is the orbital constant of earth, $J_2 = 1.08263 \times 10^{-3}$ is the quadrupole gravitational coefficient of earth, $r_{ee} = 6.378137 \times 10^6$ m is the equatorial radius of earth, and i is the inclination angle. (See Kidder and Vonder Haar (1995) for details.)

In each of the constellations discussed here, the inclination angle and the period are the same for each satellite in the constellation. The design problem for each constellation is to select (1) the semi-major axis (and thus the period), (2) the inclination angle, (3) the number and spacing of the orbital planes, and (4) the number and spacing of the satellites in each orbital

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*A*uthor addresses:* CIRA/Colorado State University, Fort Collins, CO 80523-1375, Stanley.Kidder@ColoState.EDU. Thomas.Vonderhaar@ColoState.EDU plane. In the next section, the design of four current satellite constellations is examined.

3. CURRENT SATELLITE CONSTELLATIONS

Currently, satellite constellations fall into one of two classes, navigation satellites or telecommunications satellites. Table 1 summarizes the properties of four of these constellations.

Table 1. Current constellation properties

Parameter	*GPS*	*Iridium*	*Globalstar*	*Orbcomm*
Purpose	Navigation	Telecom	Telecom	Data Comm.
Number of planes	6	6	8	4
Plane spacing (degrees)	60	30	45	45-112
Satellites per plane	4	11	6	8
Total satellites*	24	66	48	32
Orbital altitude (km)	20,181	775	1414	802
Semi-major axis (km)	26,559	7,153	7,792	7,180
Inclination (degrees)	54.8	86.4	52.0	45.0
Nodal period (min)	717.9	100.5	114.0	100.8
Satellites per launch	1	2-7	4	8

* Excluding on-orbit spares

3.1 *Navigation satellites*

The best known constellation is that of the Global Positioning System (GPS). If one knows the distance to three non-colinear points, one can calculate one's location. The GPS is a constellation of 24 satellites (plus on-orbit spares) designed such that for any point on earth, at least four satellites are above the horizon at all times. Each satellite transits information about its precise location so that receiving units on or near the surface of the earth can receive the signals and calculate their precise location. The fourth satellite allows the correction of the receiving unit's clock.

Figure 2 shows a sketch of the GPS constellation. Four satellites in each of six orbital planes form a network The semi-major axis was chosen to be large so that several satellites are above the horizon. The inclination angle was chosen so that the polar regions are well served.

Two other constellations of navigation satellites have been launched by Russia. They are the Global Navigation Satellite System (GLONASS) and a low earth orbit navigation system

3.2 *Telecommunications satellites*

The best known of the telecommunication satellite constellations is the Iridium constellation. It consists of 66 satellites (plus on-orbit spares) arranged in six orbital planes (Fig. 3). The satellites are equally spaced in each orbital plane, and the spacing in alternate planes is staggered so that the satellites form a grid. This grid (1) covers the earth, so that a ground-based receiving unit can always reach a satellite, and (2) allows satellite-to-

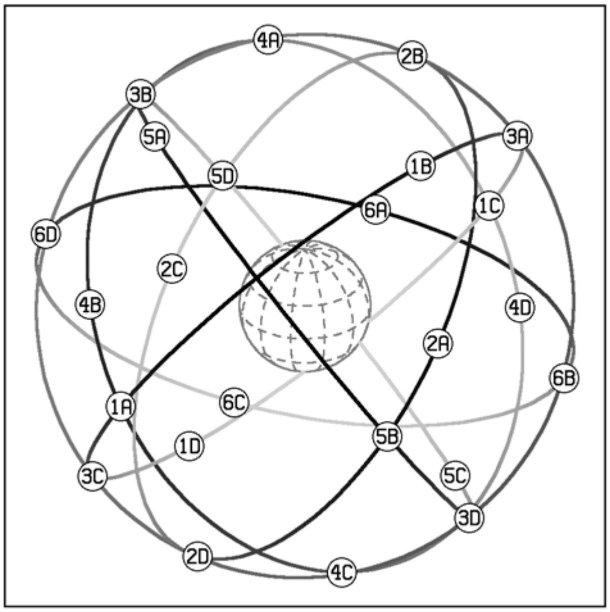

Figure 2. The GPS constellation. The satellite numbers (1 through 6) indicate the plane in which they orbit. The satellite letters (A through D) distinguish the satellites in the same plane such that the satellites are traveling in the direction from A to B to C, etc. The intensity of the orbit lines indicates distance along the line of sight; faint lines are further from the viewer.

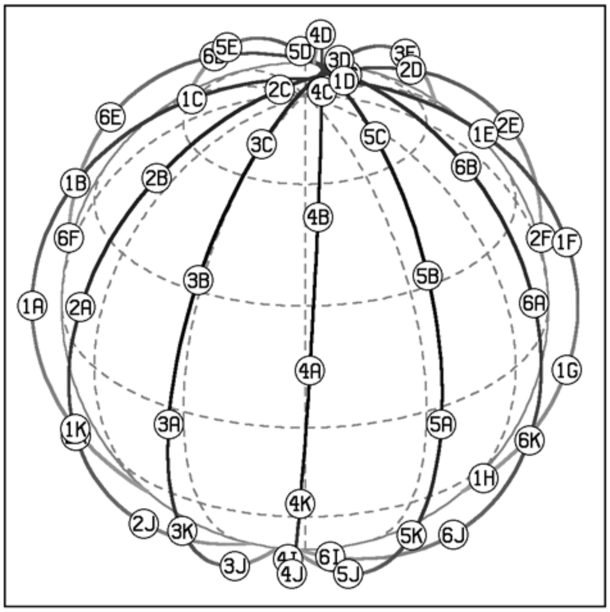

Figure 3. The Iridium constellation. As in Fig. 2, the plane of the orbit is indicated with a number; the position within the orbit and the direction of flight are indicated with letters.

satellite communication, so that a receiving unit at one point can communicate with a ground-based unit anywhere else on earth. The spacing of the planes in the Iridium constellation is exactly half that of the GPS constellation. This means that in the Iridium constellation, all the satellites in one half of the earth are traveling north, and the satellites in the other half are traveling south.

The inclination angle in the Iridium constellation was selected such that the *z*-component of the satellite's angular velocity matches the rotation rate of the earth. Thus the ground track of the satellite (the path of the intersection of the line between the satellite and the center of the earth with the earth's surface) travels directly north as the satellite ascends across the equator (Fig. 4).

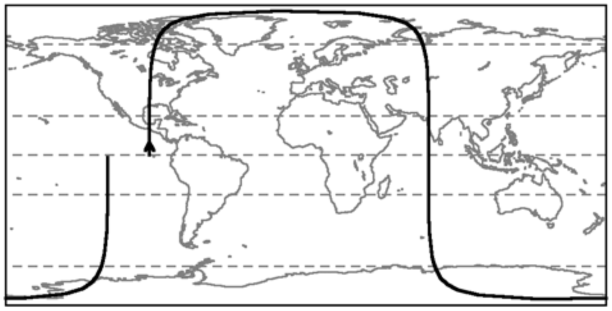

Figure 4. The ground track of a typical Iridium satellite. One complete orbit is shown. Note that the choice of inclination angle has made the motion directly north or south at the equator.

Between 2 and 7 Iridium satellites are launched on a single rocket into a particular orbital plane. After achieving orbit, the satellites are maneuvered until they are properly spaced in the orbital plane. This method achieves a considerable savings in launch costs.

A second telecommunications constellation is Globalstar. It consists of 48 satellites in 8 orbital planes (Fig. 5). Hand-held units are used at one end of the Globalstar communications chain, but the at the other end is one of a set of fixed antennas. The 52º-inclination angle provides service from 70º north latitude to 70º south latitude.

A final constellation is the Orbcomm constellation, which provides data (not voice) communications (Table 1). The constellation is not pictured here because it has irregularly spaced orbital planes. All 8 satellites in an orbital plane are launched on the same rocket.

4. A SPECTRAL RADIANCE SHELL CONSTELLATION

There are many possible ways to utilize constellations of satellites for atmospheric measurements (see, for example, Wertz and Larson 1991, pp. 171–180). To select a particular constellation, some requirements must be set. To complement traditional observations, and to adequately sample the diurnal variation of the spectral radiance shell, we require that the constellation be capable of observing every point on earth at least once per hour.

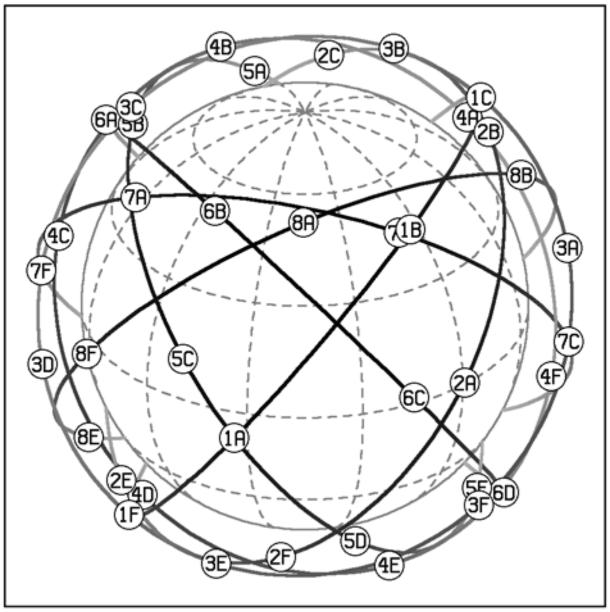

Figure 5. The Globalstar constellation.

To achieve hourly soundings, it would be convenient to place the satellite in an orbit with a 1 hr period, but this is impossible for earth (see Eq. 1). Instead, we choose to place two equally spaced satellites in an orbit with a 2 hr period. The semi-major axis of this orbit is 8,054 km, or 1,676 km above the equator—about twice as high as the current NOAA satellites. An alternate solution is to place three satellites in an orbit with a 3 hr period, but this orbit is has a semi-major axis of 10,556 km, or 4,178 km above the equator—about five times as high as the current NOAA satellites.

Because the constellation is designed to yield hourly observations, the satellites would not need to be in sun-synchronous orbits, as are the current NOAA satellites. Borrowing from the Iridium design, we choose an inclination angle of 85.2º, so that the ground track is perpendicular to the equator.

It remains, then, to choose the number of planes and the spacing between them. To achieve global coverage each hour, swaths from adjacent satellites must overlap; that is, the plane spacing can be no more than the swath width. Since the swath width (w) is related to another important parameter, the maximum viewing zenith angle (ζ), it is important to choose the plane spacing carefully. For cross-track scanners (those instruments which scan through nadir perpendicular to the satellite's motion vector) Eq. 2 relates w to ζ, and Fig. 6 shows a sketch of the geometry.

$$w = 2\left\{\zeta - \sin^{-1}\left[\left(\frac{r_{ee}}{r}\right)\sin\zeta\right]\right\} \tag{2}$$

The Advanced Very High Resolution Radiometer (AVHRR) instrument on the current NOAA satellites has a maximum viewing zenith angle of 69º. For w = 45º, at the height of a satellite in a 2 h period orbit, ζ = 71º, which is only 2º worse than the current AVHRR. Thus four orbital planes spaced 45º would deliver approximately the same image quality as the current AVHRR instrument. The properties of this constellation are shown in Table 2 and sketched in Fig. 7.

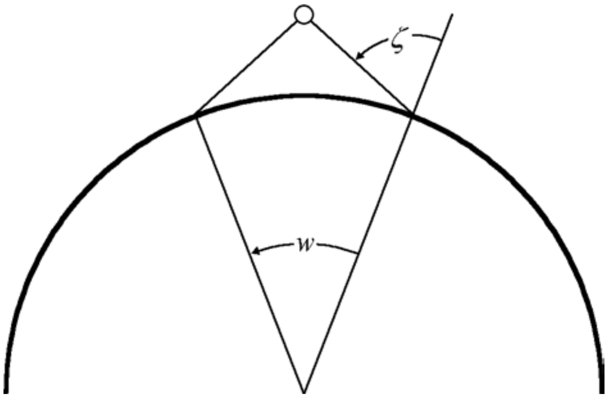

Figure 6. The relationship between swath width (w) and maximum viewing zenith angle (ζ).

Table 2. Properties of one possible spectral radiance shell constellation

Parameter	*Value*
Purpose	Spectral radiance shell observations
Number of planes	4
Plane spacing (degrees)	45
Satellites per plane	2
Total satellites	8
Orbital altitude (km)	1,676
Semi-major axis (km)	8,054
Inclination (degrees)	85.2
Nodal period (min)	120
Satellites per launch	2

The instruments with the narrowest swath widths are the conical microwave scanners, such as the Conical Microwave Imager/Sounder (CMIS) that will fly on the satellites in the National Polar-orbiting Observational Environmental Satellite System (NPOESS). These instruments would require up to seven planes and 14 satellites to form a 1 h constellation with no gaps.

The constellation detailed in Table 2 would be capable of observing the spectral, spatial, and temporal variations of the spectral radiance shell. The angular variations would have to be observed over a period of time as each point is viewed by different satellites at different angles.

5. DISCUSSION

An obvious question is, why not simply launch more sun-synchronous satellites to achieve the same goal? A constellation of seven sunsynchronous satellites in orbits similar to the current NOAA and DMSP satellites is sketched in Fig. 8 and detailed in Table 3.

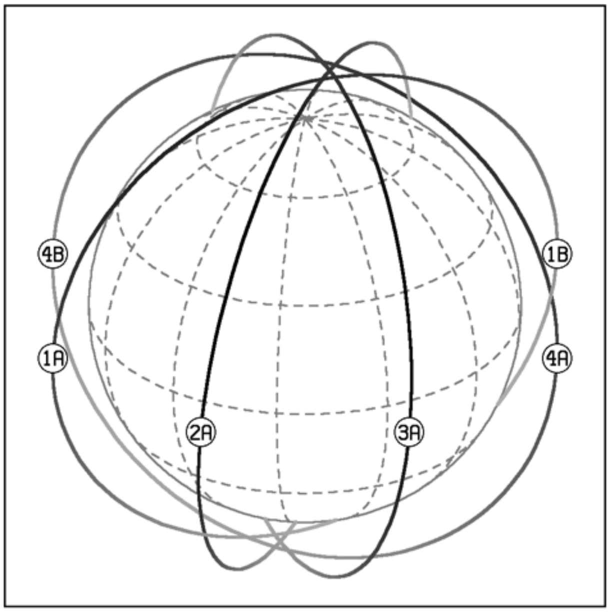

Figure 7. A possible spectral radiance shell constellation. As in the Iridium constellation, satellites on one side of the earth (the A satellites) are traveling north and on the other side (the B satellites), south. In this sketch, all the satellites are at the equator; 30 min later, the A satellites will be clustered near the North pole, and the B satellites will be near the South Poles. The height of the orbit and the number of planes has been chosen such that there are no gaps in coverage between the satellites; thus, the entire earth is sensed once each hour.

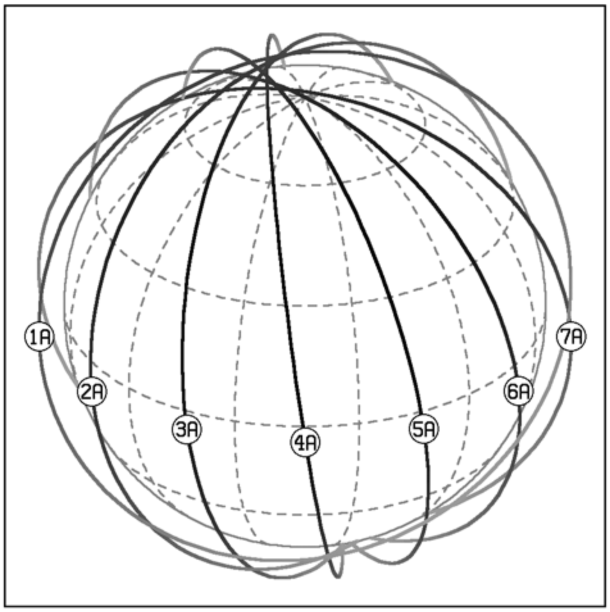

Figure 8. A constellation of sunsynchronous satellites. Only one satellite is in each orbital plane.

Table 3 Properties of a sunsynchronous constellation

Parameter	*Value*
Purpose	Spectral radiance shell observations
Number of planes	7
Plane spacing (degrees)	25.7
Satellites per plane	1
Total satellites	7
Orbital altitude (km)	850
Semi-major axis (km)	7,228
Inclination (degrees)	98.7
Nodal period (min)	101
Satellites per launch	1

Because current sunsynchronous satellites are closer to the earth than those in the proposed spectral radiance shell constellation, the swath width is smaller, and the number of planes necessary to achieve contiguous coverage is greater, seven versus four. Also , if only one satellite is in each plane, the temporal coverage is less (101 min versus 60 min). Finally, with only one launch per plane, launch costs would be greater. The spectral radiance shell constellation would require eight satellites and four launches. The sunsynchronous constellation would require seven satellites and seven launches. An advantage of the sunsynchronous constellation is that the satellites would receive less radiation than those in the spectral radiance shell constellation and, thus, would require less radiation hardening.

Another question is, why not use a combination of geostationary and low earth orbiting satellites to observe the spectral radiance shell? This is currently being done and has been done for many years. Some of the drawbacks are that this system is composed of a wide variety of instruments and capabilities, which, again, means that that the spectral radiance shell is sparsely observed. Geostationary satellites have fewer spectral bands (and will not have microwave measurements for many years). Also, geostationary satellites observe each point from only one angle. Low earth orbiters, which fly under the geostationary satellites, have many more spectral bands, but much poorer temporal resolution. Also, each sunsynchronous satellite samples only two local times. Thus, a combination of geostationary and low earth orbiting satellites cannot provide as complete a picture of earth’s spectral radiance shell as can a constellation of satellites designed specifically for such observation.

6. SUMMARY AND CONCLUSIONS

It has been shown that a constellation of eight satellites can make hourly observations of the spectral radiance shell of earth at all latitudes and longitudes. Satellite constellations have not been employed for earth remote sensing as they have been in the telecommunications and navigation fields. Perhaps it is time to explore their unique capabilities.

Acknowledgments

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