Understanding the Imaging Capability of Tundra Orbits Compared to Other Orbits

Zhenglong Li, Timothy J. Schmit, Jun Li, Mathew M. Gunshor, and Frederick W. Nagle

***Abstract*— For operational weather forecasting and nowcasting, a refresh rate (RR) of 10 min and a better-than-4-km footprint size for Infrared (IR) bands is desired. Such imaging capability is only available from geostationary orbit (GEO) satellites, such as ABI onboard geostationary operational environmental satellites (GOES)-16/-17, but mainly limited to the tropics and mid-latitudes (referred to as GEO-like imaging capability). For high latitudes such as the Alaskan region, the IR footprint size from ABI/GOES-17 is worse than 6 km, limiting the application over the region. Tundra satellites, with a nonzero inclination angle and a nonzero eccentricity, have longer dwell times near the apogee than the perigee and can be used to monitor the high latitudes and polar regions. This study investigates Tundra satellites' imaging capability by assuming an ABI-like instrument with the same IR spatial resolution of 56 μrad onboard. For regional applications, a constellation of two Tundra satellites may provide GEO-like imaging capability for a large domain. This useful domain is further improved when combined with a GEO, i.e., two Tundra+GOES-17. For global applications, a constellation of three Tundra satellites may provide GEO-like imaging capability for high latitudes (improved capability over GEO) and polar regions (unprecedented capability) in both hemispheres. The additional capability from Tundra satellites in tropics and mid-latitudes makes the global space-based meteorological observing system more robust and resilient. While a constellation of three Tundra + 3 GEOs may provide global GEO-like imaging capability, having more than three GEOs may be desired by agencies/countries, allowing for improved spatial resolutions over their sub-point locations.**

***Index Terms*— Fire detection, high latitude, imaging capability, polar region, Tundra orbits, weather forecasting.**

I. Introduction

For operational meteorological satellites, there are commonly two types of orbits in use: the geostationary orbit (GEO) and the low earth orbit (LEO). GEO is one type of geosynchronous orbits with a period of 24 h and an inclination angle of 0°. Because of the 24-h period (same as earth rotation period) and 0° inclination angle, a GEO satellite has a fixed nadir location on the Equator. A GEO satellite is capable of providing full temporal coverage within its spatial domain. GEO has a high altitude of 35 800 km, so GEO spatial coverage is relatively large. The maximum in full-disk mode covers about 1/3 of the earth surface. For example, the advanced baseline imager (ABI) on the current geostationary operational and environmental satellites (GOES-R) [1] observes the atmosphere and the earth surface every 10 min in the full disk in mode six. Currently, the two-satellite duo of GOES-16 and -17 together provide Infrared (IR) imagery observations of the development of the atmospheric moisture and clouds in North/South Americas, and much of the Atlantic and Pacific Oceans. Such information is critical for short-term weather forecasting and nowcasting. The data are also used in numerical weather prediction (NWP) model assimilation. The constellation of international GEO satellites provides full temporal coverage of the whole tropics and mid-latitudes. The usefulness in high latitude, although partially covered, is hindered, due to increased spatial resolution. GEO satellites provide little capability in polar regions.

The data gap in high latitudes and polar regions left by GEOs can hardly be mitigated by LEOs. In satellite meteorology, LEO is usually used for what should be called the sun synchronous orbit (SSO), which is one special type of LEO, with an inclination angle of about 98°. It is called SSO because this inclination angle allows the satellites to pass the Equator at a fixed local time, i.e., National oceanic and atmospheric administration (NOAA)-20 at 1:25 pm in ascending mode and Metop-A/B/C at 9:30 am in a descending mode. LEO has much lower satellite altitude (about 800 km) than GEO. So, LEO sensors usually have much finer spatial resolution than GEO for IR bands, i.e., 750 m from VIIRS/NOAA-20 and 2 km from ABI/GOES-16. With an inclination angle close to 90°, LEO satellites fly between the two poles, resulting in global spatial coverage. Thus, LEO is capable of providing very high-resolution observations globally, a big advantage over GEO, making it particularly useful for global NWP and climate applications. The disadvantage, though, is the much-reduced observation frequency, or refresh rate (RR). For example, VIIRS revisits the same location twice a day in tropical regions, an RR of about 12 h. At the poles, the RR is about 100 min. In between, the RR is somewhere between 100 min and 12 h, depending on the latitude. For short-term weather forecasting and nowcasting in high latitudes and polar regions, RR of 100+ min is far from enough to meet the requirement. Although the multiple satellite constellation improve the RR to some extent, there would need to be an unrealistic number of

Manuscript received October 20, 2020; revised December 15, 2020; accepted January 7, 2021. This work was supported in part by the National Environmental Satellite, Data, and Information Service (NESDIS) Office of Projects, Planning, and Analysis (OPPA), Technology Maturation Program (TMP) and the Geostationary Extended Observations (GEO-XO) Program NA15NES4320001. *(Corresponding author: Zhenglong Li.)*

Zhenglong Li, Jun Li, Mathew M. Gunshor, and Frederick W. Nagle are with the Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin–Madison, Madison, WI 53706 USA (e-mail: Zhenglong.li@ssec.wisc.edu).

Timothy J. Schmit is with Advanced Satellite Products Branch, National Oceanic and Atmospheric Administration/ Center for Satellite Applications and Research, Madison, WI 53706 USA.

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TGRS.2021.3051527.

Digital Object Identifier 10.1109/TGRS.2021.3051527

LEO satellites to achieve 10-min imaging capability, especially for high latitudes such as Alaska, as will be demonstrated by this study. With recent developments in CubeSat technology [2], it is possible to launch a large number of cost-effective smaller satellites to potentially fill the GEO data gap in high latitudes and polar regions.

With the increasing interest in polar regions, as a result of melting sea ice and other reasons, the World Weather Organization (WMO) has endorsed the use of the highly elliptical orbit (HEO) to fill the data gap left by GEO [3]. An HEO is an elliptical orbit with high eccentricity. The advantage of HEO is its longer dwell times near apogee than perigee. By placing the apogee over a certain region, HEO may provide full temporal coverage of the area during the approach to and descent from the apogee. HEO orbits usually have periods of 12–24 h. There are two special HEO orbits: the Molniya orbit, with a period of 12 h and an inclination angle of 63.4° (the so-called critical inclination angle), and the Tundra orbit, with a period of 24 h. Both orbits have been used for communication purposes in high latitudes. The main difference is that Tundra satellites observe one single fixed region of the earth near the apogee, while Molniya satellites observe two fixed regions (180° of longitude apart). Other HEO orbits with periods between 12 and 24 h usually have multiple observation regions, which may be beneficial for broader regional applications, such as the whole Arctic region.

There are several HEO missions that have been studied or are being studied in support of weather and environment applications, including Canada's Polar Communications and Weather Satellite (PCW) mission [4], Canada's Atmospheric Imaging Mission for Northern Region (AIM-North) [5], and Russia's Arktika network [6]. Many studies have investigated the feasibility of HEO for high latitudes and polar regions, including frozen orbits [7], spatial and temporal samplings [8], NWP model impact study using observing system simulation experiment (OSSE) study [4], and constellation imaging capacity [9]. Most of these studies focus on orbits with periods of 12–16 h, i.e., Molniya orbits [10], [11], 14–15 h [11], and 16 h [12]. One important risk of HEO orbits is the impact of the ionizing radiation [13], [14]. As HEO satellite altitudes range from thousands to tens of thousands of kilometers, they may enter and exit the Van Allen radiation belt multiple times during each period. The thickness of the aluminum slab shield has been studied for various HEO orbits in order to protect the satellites and the payloads from the trapped protons and electrons within the radiation belt [13], [14].

To support the NOAA Satellite Observing System Architecture (NSOSA) Study [15], as part of investigating the possibility for moderate disaggregation of the LEO constellation, this study extends existing studies with a focus on the Tundra orbit for high latitudes and polar regions, as a possible candidate to fill the data gap left by GEO. The Tundra orbit is uniquely different from GEO and LEO and is characterized by three key features [7]: geosynchronous period, nonzero inclination angle, and nonzero orbital eccentricity. The long geosynchronous period of 24 h offers the possibility for Tundra satellites to observe the earth from high altitude, thus a large spatial coverage from a full disk scan, similar to GEO. The period of exactly 24 h allows the daily repeat of the satellite nadir track on the ground, ideal for regional applications. The nonzero inclination angle allows the Tundra satellites to fly between Southern and Northern Hemispheres, which increases the global coverage, similar to LEO. There are two special inclination angles for Tundra satellites: 90°–63.4°. The 90° inclination angle has the advantage of being least affected by the precession of the orbital plane [8], and the critical inclination angle has the advantage of being least affected by the secular precession of the perigee. The nonzero orbital eccentricity allows Tundra satellites to spend more time near their apogee than perigee. This unique advantage is not available from GEO or LEO, both of which have an eccentricity of 0, or a circular orbit. In this study, the Tundra eccentricity is set to 0.2684. This eccentricity is chosen to allow Tundra satellites to have twice as much dwell time in the apogee hemisphere (16 h during one period) than the perigee hemisphere (8 h during one period). Larger eccentricity may further increase the dwell time in the apogee hemisphere. But the increased apogee distance and reduced perigee distance may increase the risk from the ionizing radiation.

Tundra satellites can be used for many applications, such as short-term weather forecasting and nowcasting, NWP, sea ice coverage, volcano/fire/hot spot monitoring, aurora imaging, etc., This study investigates the potential advantages and disadvantages of Tundra orbits for monitoring, nowcasting, and forecasting the high impact events in high latitudes. Specifically, this study focuses on assessing the imaging capability by placing the ABI on Tundra satellites. Imaging capability will be quantified and compared with ABI/GEO and VIIRS/LEO, from a single as well as a constellation of multiple Tundra satellites. The needs of the National Weather Service (NWS) for satellite imagery include an RR of 10 min and a footprint size of 4 km or better. Two criteria, data continuity (DC) with emphasis on RR, and effective footprint size (EFS) with emphasis on spatial resolution, will be used to quantify the imaging capability, for both global and regional applications.

This manuscript is organized as follows. Section II introduces the Tundra simulation capability, including the orbit simulator, navigation simulator, and radiance simulator. Section III compares the footprint size between Tundra, GEO, and LEO. Section IV demonstrates the imaging capability from Tundra, GEO, and LEO, from single or constellation of multiple satellites, for regional and global applications. Section V provides a summary and discussion. To avoid confusion, the earth's surface is categorized into seven regions.

1) Northern polar region: [67.5°N 90°N].
2) Northern high latitudes: [45°N 67.5°N].
3) Northern Mid-latitudes: [22.5°N 45°N].
4) Tropics: [22.5°S 22.5°N].
5) Southern Mid-latitudes: [45°S 22.5°S].
6) Southern high latitudes: [67.5°S 45°S].
7) Southern polar region: [90°S 67.5°S].

II. ABI/Tundra Radiance Simulation

To assess the Tundra imaging capability, the ABI with the same scan configuration as those on GOES-16/-17, is assumed to be onboard Tundra satellites with the 10-min flex

TABLE I
SOME ORBITAL PARAMETERS FROM TUNDRA, GEO, AND LEO

	Geosynchronous		Sun Synchronous
	Tundra	GEO	LEO
Period	24 hours	24 hours	~100 minutes
Inclination (°)	≠0 (i.e., 90 or 63.4)	0	~98
Eccentricity	0.2684	~0	~0
Altitude (km)	[24,552 47,224]	35,800	~800

mode (mode 6), or one full disk every 10 min. This allows the assessment of Tundra's imaging capability using existing sensor technology. To simulate all-sky ABI/Tundra radiances, the atmospheric fields, and the surface conditions from a nature run (NR), along with the viewing geometry, are needed. That requires three accurate components: the orbit, the navigation, and the radiance simulation.

A. Orbit Simulator

In previous studies [16], [17], the University of Wisconsin–Madison has developed the capability to simulate LEO satellite radiances for existing and future satellite sensors, including SSO and other LEO, such as Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) with an inclination angle of 30° [2]. A new orbit simulator was developed to simulate HEO orbits. HEO is significantly different from LEO with a much longer period. The input of the orbit simulator is six orbital parameters, including period, inclination angle, right ascension of the ascending node (RAAN), an argument of perigee, eccentricity, and mean anomaly. The orbit simulator provides satellite location (latitude, longitude, and altitude) for any given time. Table I shows some of the key orbital parameters for the specific Tundra orbit investigated, along with GEO and LEO for comparison. The nonzero inclination and eccentricity ensure longer dwell times over apogee area than perigee one, the biggest advantage of a Tundra orbit. It is important to point out that the altitude is determined once the period and eccentricity are determined. The high altitudes make it possible to have full-disk scanning of the earth and atmosphere. For this study, one day of orbits was simulated for July 1, 2006.

B. Navigation Simulator

The ABI onboard the GOES-R series has a fixed spatial resolution of 56 μrad for the IR bands and fixed grid coordinates with viewing angle increase between two consecutive pixels being 56 μrad in both east-west (EW) and north-south (NS) directions [18]. For GEO with an altitude of 35,800 km, that results in a spatial resolution of 2 km and a pixel-to-pixel distance of 2 km at the nadir. The ABI in 10-min flex mode scans a full disk every 10 min. To simulate the Tundra imaging capability, the same ABI is assumed to be onboard Tundra satellites with the 10-min flex mode. Compared to fixed grid coordinates from GEO, due to the constantly changing nadir location, Tundra satellites do not have a fixed navigation system on the earth surface (i.e., the latitude and longitude of each grid point), although the satellite viewing angle and azimuth angle are exactly the same as GEO. To accurately simulate ABI/Tundra radiances, a navigation simulator was developed to simulate the HEO satellite and solar geometries, including latitude, longitude, satellite zenith angle, satellite azimuth angle, solar zenith angle, and solar azimuth angle of each grid point. The navigation is simulated to have a full disk scan every 10 min. However, due to the altitude change, Tundra satellites do not always have a successful full disk scan of the earth. For example, at the perigee, where Tundra altitude is smallest (about 24,500 km, see Table I), a maximum scan angle (MSA) of 12° in both forward/rear and left/right (FRLR) directions would be needed in order to have a completely full disk scan, while ABI/GOES-R series only has an MSA of about 8.7° [18]. This results in a reduced coverage from Tundra near perigee. This limitation may be mitigated by increasing the number of detectors.

C. Radiance Simulator

To simulate ABI/Tundra radiances, the atmospheric field (T/Q/O_3 and clouds) and surface conditions are needed as input for the radiative transfer model (RTM) calculations. Such information usually comes from NWP model simulations. Any NWP models with such information and adequate spatial and temporal resolutions can be used. In this study, the Goddard Earth Observing System Model Version 5 Nature Run (G5NR) [19], a two year global, nonhydrostatic mesoscale simulation, with a spatial resolution of 7 km and a temporal resolution of 30-min, are used as an example to show how ABI/Tundra radiances look like. Note that ABI/Tundra has higher temporal and spatial resolutions than G5NR. The latter is temporally and spatially interpolated to ABI pixels to generate the atmospheric field and surface conditions every 10-min. The all-sky ABI/Tundra radiances are then simulated with the Community Radiative Transfer Model (CRTM) V 2.1.3 with Optical Depth in Pressure Space (ODPS) coefficients [20] with the geometry from the navigation simulator.

Fig. 1 shows two examples of simulated ABI/Tundra radiances (inclination angle of 90°) when the satellite is right above the poles, along with ABI/GOES-17. This Tundra orbit is specially designed for the Alaskan region (see SAT-1 in Table II for orbital parameters). When this Tundra satellite is at the perigee above the South Pole, its altitude of 24,552 km is lower than the geostationary altitude of 35,800 km. That results in reduced coverage from the full disk with an MSA of 8.7°. However, it still has a full coverage of the south polar region, almost a full coverage of the southern high latitudes, and limited coverage of the southern mid-latitudes. At the apogee above the North Pole, with a higher altitude of 47,224 km, this Tundra satellite produces a full disk scan of the earth and atmosphere, completely covering the north polar region, the northern high latitudes, and the north mid-latitudes.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

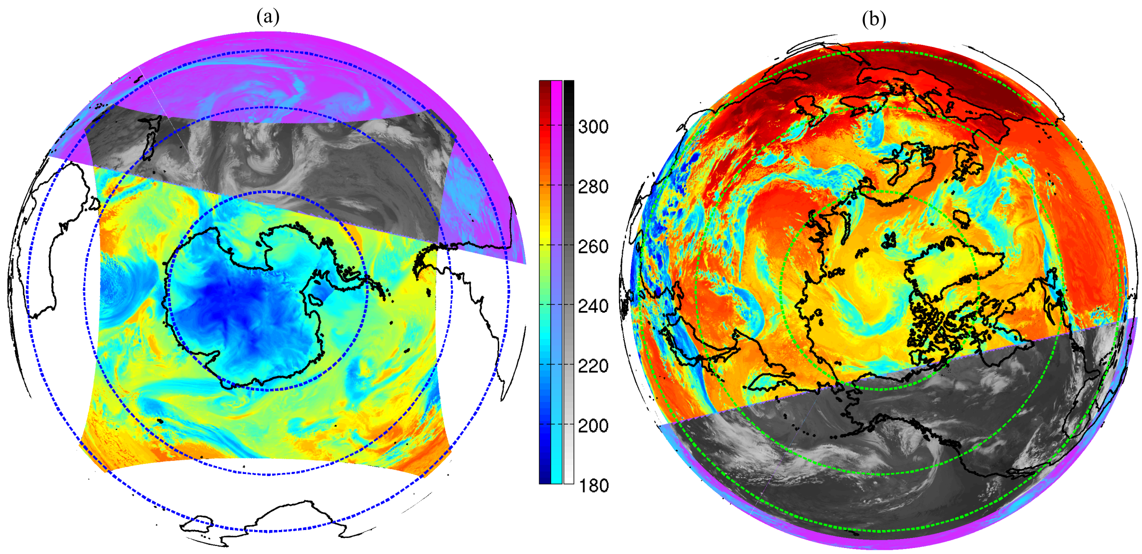


Fig. 1. Simulated 11.2 μm brightness temperature (K) of ABI/Tundra and ABI/GOES-17 precisely at (a) perigee above the South Pole at 00:20 UTC and (b) apogee above the North Pole at 12:20 UTC on July 1 2006. The blue/red color bar is for ABI/Tundra, the light blue/purple color bar is for ABI/GOES-17, and the gray color bar is for the overlap region. The dashed blue/green lines denote the boundary between polar regions, high latitudes, mid-latitudes, and tropics. A threshold of 80° of local zenith angle is applied to remove pixels with extremely large footprint size.

TABLE II
ORBITAL PARAMETERS FOR TUNDRA SATELLITES USED IN THIS STUDY

Simulated Satellites	Period (h)	Inclination angle (deg)	RAAN (deg)	Argument of perigee (deg)	Eccentricity	Mean anomaly (deg)
SAT-1	24	90	225	270	0.2684	355
SAT-2	24	90	45	270	0.2684	175
SAT-3	24	45	225	270	0.2684	355
SAT-4	24	45	45	270	0.2684	175
SAT-5	24	90	225	150	0.2684	355
SAT-6	24	90	225	30	0.2684	355

GOES-17, with symmetry, has the same coverage in both hemispheres, including little coverage of the polar region, a decent coverage of the high latitudes, and great coverage of the mid-latitudes. From Fig. 1, it appears that GOES-17 may be used for applications in high latitudes like the Alaska region. The coarser footprint size with increased local zenith angle hinders such applications, as will be demonstrated in this study. Although, the GEO may provide the time tendencies over this region.

III. Footprint Size Comparison

One important parameter to characterize the imaging capability is the footprint size. Smaller footprint size is desired to resolve smaller scale phenomena, such as small scale convections, fires, volcanoes, and turbulence. Fig. 2 shows the footprint size imagery for ABI/Tundra (SAT-1) and ABI/GOES-17 at 12:20 UTC on July 1, 2006, as well as the time series for two locations: nadir and Fairbanks, Alaska (latitude of 64.84°N and longitude of 147.72°W). The ABI/Tundra full disk has a similar footprint size pattern as GEO. The nadir has the smallest footprint size since it is closest to the satellite and has the smallest local zenith angle. The footprint size increases with increased distance away from the nadir. At this particular time, the Tundra nadir is right at the North Pole, and the whole northern polar region and northern high latitudes have a footprint size smaller than 4.3 km. Specifically, the Alaskan region is fully covered with a footprint size better than 4 km. As a comparison, the ABI/GOES-17 footprint size is mostly larger than 4 km for northern high latitudes and the polar region. For the Alaskan region, the footprint size is larger than 6 km and degrades rapidly toward the north. The large footprint size over Alaska hinders the applications for the region.

One advantage of the Tundra orbit is its longer dwell times over the apogee hemisphere or the northern hemisphere in this particular case. This allows a longer period of high-quality imagery observations near its apogee, as can be seen from Fig. 2(c). Fairbanks is observed by the Tundra satellite from 4:20 to 20:20 UTC. Among the 16 h, the footprint size is smaller than 3.05 km from 6:20 to 18:20 UTC. For the consecutive 12 h, the footprint size is relatively stable. These results indicate that one Tundra satellite may provide stable high-quality imagery observations of the Alaskan region for a consecutive half of a day. By comparison, ABI/GOES-17 observes Fairbanks continuously, but with a rather coarse footprint size of 7.9 km, greatly hindering the applications in the region.

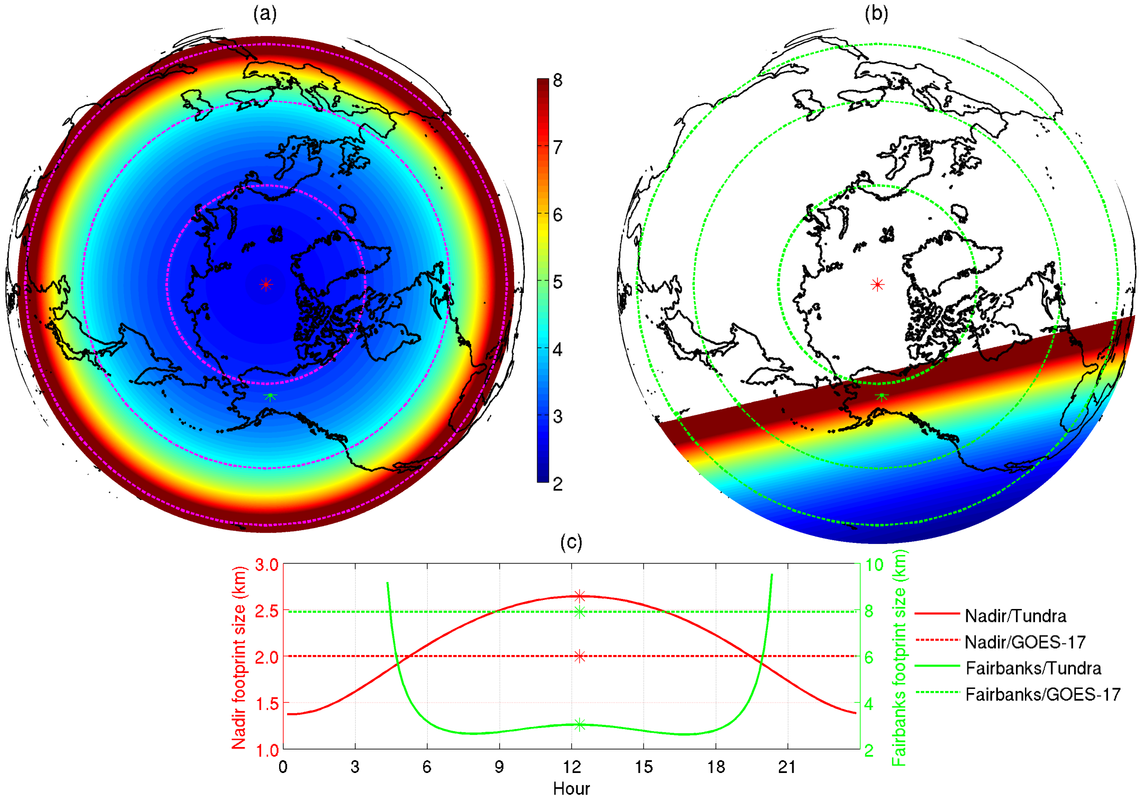


Fig. 2. Footprint size (km) of (a) ABI/Tundra, (b) ABI/GOES-17 at 12:20 UTC on July 1 2006, and (c) time series of the footprint size of nadir and Fairbanks Alaska for ABI/Tundra and ABI/GOES-17. The nadir is marked with a red star in (a) and (b), and Fairbanks with a green star. Note the coordinate scales differ between the nadir and Fairbanks locations. The purple and green dashed lines in (a) and (b) denote the boundaries between polar regions, high latitudes, and mid-latitudes. The stars on the lines in (c) correspond to 12:20 UTC. A threshold of 80° of local zenith angle is applied to remove pixels with extremely large footprint size.

It is also noted that the footprint size of ABI/Tundra nadir is temporally variable. It is 1.38 km at the perigee and 2.63 km at the apogee. This does not necessarily mean Tundra satellites provide better observations near perigee. That is because the dwell times near perigee are much shorter than those near apogee. Also, as shown in Fig. 1, the spatial coverage near the perigee is reduced due to the limitation of its MSA. If there were fires/hot spots at the latitude of 64.84°S (same latitude as Fairbanks but in the Southern Hemisphere), the ABI/Tundra would only be able to monitor it for a maximum of about 4.5 h with a footprint size better than 3.05 km. This is much reduced compared to Fairbanks' 12 h.

IV. Imaging Capability Comparison

Fig. 2 is useful for comparing footprint sizes from two satellites at a specific location based on a single time step, thus for instantaneous comparison. However, the Tundra orbits are more complicated than GEO because of constantly changing satellite location and altitude. So, the results from the instantaneous comparison might not be applicable to other times and locations. For example, it is not immediately clear which satellite provides better imagery observations over the northern Pacific off the coast of Alaska. Since it is further away from the Tundra's apogee location, the footprint size is expected to increase with reduced temporal coverage. GOES-17, on the other hand, should see a finer footprint size since it is closer to the nadir. It is, therefore, not practical to determine which platform provides better quality of imagery observations, or imaging capability, just based on instantaneous comparisons.

To better understand and quantify the Tundra's overall imaging capability, and help compare with GEO and LEO, two parameters are developed for each location: the DC and the EFS. DC, characterizing temporal coverage in percentage, is defined as the ratio of the number of time steps when there are observations of the total number of time steps regardless of whether there are observations or not. To get rid of the time dependence, DC is calculated for 24 h or Tundra's period. DC is affected by the total number of time steps within 24 h or the RR. Since ABI on both Tundra and GOES-17 is assumed to be in mode 6, or 10 min for a full disk scan, the total number of time steps is 144. A DC of 50% means for 50% of the time, or 72 time steps, the location is observed. When DC is 100%, it means that the location has full temporal coverage or is time continuously observed. Apparently, GEO's DC is either 100% within the domain or 0% outside the domain.

DC characterizes how *often* satellites observe. EFS characterizes how *well* satellites observe. It is defined as the EFS of each location, for 24 h to get rid of the time dependence. Its calculation is based on the principle that how many independent observations within the unit area (i.e., 100 km^2).

If there are multiple observations of the same location at the same time, EFS should be smaller than any of the footprint sizes of those observations. If there are multiple time steps observing the same location, EFS should be larger than the smallest and smaller than the largest footprint sizes of those observations. EFS is calculated through two steps. When there are multiple independent observations of the same location from different satellites at the same time, the resulting footprint size is calculated using

$$R^i = \frac{1}{\sqrt{\left(\sum_{j=1}^{n} \frac{1}{r_j^{i2}}\right)}} \tag{1}$$

where R^i is the resulting footprint size for time step i, and r_j^i is the footprint size from jth observation at time step i, and n is the number of observations at time step i. The EFS is then calculated using

$$\text{EFS} = \sqrt{\frac{m}{\sum_{i=1}^{m} \frac{1}{R^{i2}}}} \tag{2}$$

where m is the number of time steps when there are observations.

These two criteria have some advantages allowing the comparison of different satellite platforms quantitatively and objectively. First, as pointed out, it is independent of time since both criteria are calculated for a period of 24 h. Second, both criteria are calculated on global grid points, thus allowing the comparison of different satellite platforms for different locations. While it is configurable, the grid point is set to 2° for both latitude and longitude. Third, the two criteria are independent of each other and can be plotted together on one figure to provide a comprehensive depiction of the imaging capability of different satellite platforms, such as a single satellite or a constellation of multiple satellites, or even the combination of satellites from different platforms, to determine if they meet user needs. It is important to point out that the calculated EFS is a little overestimate of the real achievable footprint size. This is because there are not multiple independent pieces of information when there are multiple independent observations of the same target. One additional limitation of the two defined criteria is that they provide no information on individual time steps. Thus, better DC and EFS do not necessarily mean all time steps are better.

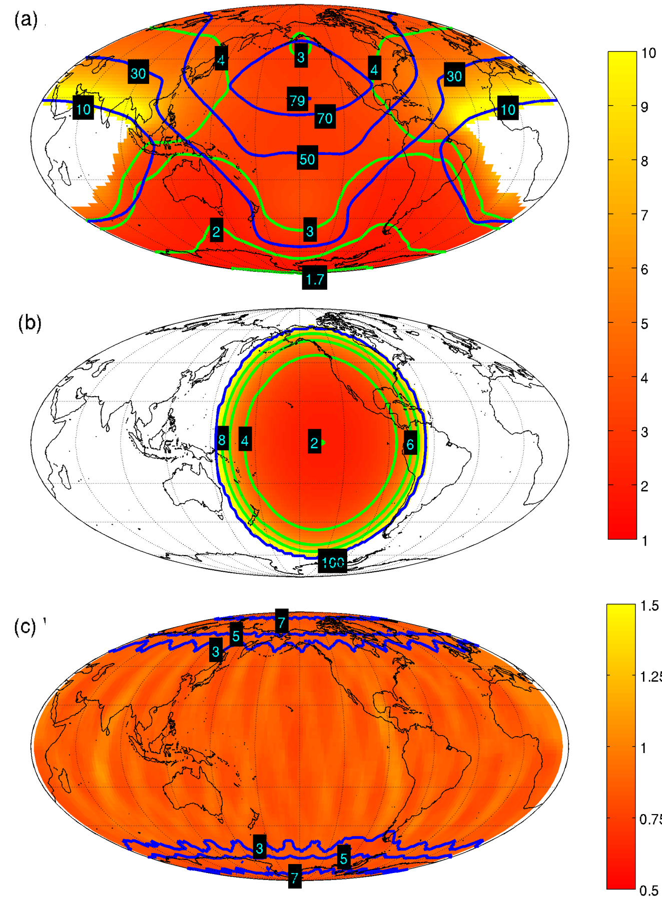


Fig. 3. Effective footprint size imagery of a single satellite from (a) ABI/Tundra, (b) ABI/GOES-17, and (c) VIIRS/SNPP. The contours of (green lines) EFS and (blue lines) DC are also shown. The contour of VIIRS/SNPP EFS is not shown because it is significantly better than ABI/Tundra and ABI/GOES-17. Note VIIRS/SNPP has a different color bar. Local zenith angle larger than 80° is not used in the calculation of EFS and DC. The center longitude of the imagery is 150°W. The horizontal black dashed lines denote the boundaries between polar regions, high latitudes, and mid-latitudes.

A. Single Tundra Satellite

To help understand the advantages and disadvantages of Tundra orbits, the single satellite scenario is compared with GEO (GOES-17) and LEO (VIIRS/SNPP), and the DC and EFS are shown in Fig. 3. Note this Tundra satellite uses the same orbital configurations as those shown in Figs. 1 and 2 (SAT-1 in Table II).

Fig. 3 clearly shows the limitation of GEO and LEO in high latitudes and polar regions. GEO has full temporal coverage within its fixed domain in tropics, mid-latitudes, and high latitudes. But the EFS degrades rapidly approaching high local zenith angles. For the Alaskan region, the EFS is larger than 6 km, substantially larger than NWS needs, limiting its applications. Although a constellation of multiple GEOs may increase its global spatial coverage, it will not mitigate the EFS gap in much of high latitudes and polar regions. LEO has global coverage and great EFS, mostly better than 1 km. However, its DC is smaller than 3% for the whole tropic and mid-latitude regions, and much of the high latitudes. The DC increases from the Equator to the poles. The Alaskan region has a DC of about 3% to 5%. Using the mean DC value of 4% to represent the Alaskan region, it would take a constellation of at least 25 LEO satellites to have full temporal coverage of the area. The maximum DC of 10% is located at the poles and their surroundings. That’s reasonable because LEO satellites revisit the poles about every 100 min. To achieve full temporal coverage of the poles, it would take a constellation of at least 10 LEO satellites. These results indicate that both GEO and LEO, as well as their constellations, do not have the needed imaging capability for the high latitudes and polar regions. Of course, LEO orbits do provide global coverage, which is used for many applications.

Tundra satellites have some of the advantages of both GEO and LEO, making them suitable for imaging the high latitudes and polar regions. From Fig. 3, a Tundra satellite has a near-global spatial coverage because it flies between the southern and northern hemispheres. Its coverage is much larger than a GEO and slightly smaller than a LEO. The spatial gap can be mitigated from a constellation of multiple Tundra satellites, as will be demonstrated in Section IV-C.

Within its domain, a Tundra satellite has a much better temporal coverage than a LEO. Almost anywhere it observes, its DC is better than 10%. This particular Tundra satellite observes the northern hemisphere much more frequently than the southern hemisphere. More than half of the time, it observes a quite large domain, including North America, northern Pacific, northeast Asia, and the northern polar region. There is less temporal coverage over the rest of the world. It is interesting to point out that the most frequently observed location (about 80%, inside the contour of 79%) around (20°N, 150°W) by this Tundra satellite is not the North Pole, although that is the location with the longest nadir dwell times near the apogee. Almost the whole southern hemisphere has a DC worse than 50%, due to the less dwell times from the perigee hemisphere. Although this Tundra orbit is optimized for the Alaskan region, it actually is optimized for the longitude of 150°W. That longitude is much more frequently observed than any other longitudes. The opposite of it or the longitude of 30°E is least observed. The gap left by one single Tundra satellite in southern Africa centers along the longitude of 30°E.

The northern hemisphere has overall larger EFS than the southern one because of higher Tundra satellite altitudes in the apogee hemisphere. Most of the southern hemisphere has an EFS better than 4 km except near the domain edge. Much of it is better than 3 km. The finest EFS about 1.7 km, not surprisingly, is located in the southern polar region. The whole northern hemisphere has an EFS larger than 3.0 km. But it has a relatively large domain with an EFS better than 4.0 km, including the middle and northern Pacific, most of North America, northeast Asia, and the northern polar region. Most of this better-than-4.0-km domain has a DC better than 50%.

These results indicate that no single satellite from the three platforms has good enough imaging capability, as there are still many temporal and/or spatial gaps left. However, it is obvious that Tundra satellites have the potential imaging capability for both regional and global applications that cannot be achieved by a constellation of a realistic number of GEOs or LEOs. For regional applications, one may configure a two Tundra constellation so that both satellites have exactly the same nadir track but the lag of each other by 12 h. This way, there is at least one satellite observing the desired region, i.e., the Alaskan region. This region is also configurable by adjusting the RAAN and the inclination angle. For global applications, one may configure a three Tundra constellation to increase the temporal coverage of polar regions and high latitudes in both hemispheres.

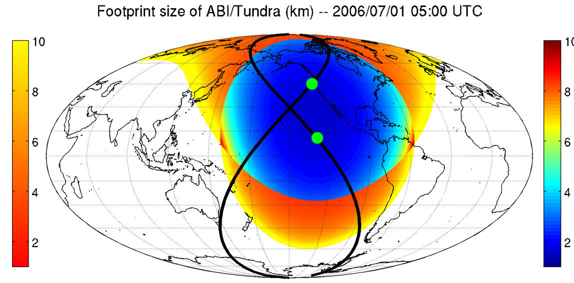


Fig. 4. Footprint size imagery of a two-satellite Tundra constellation at 5 UTC on 01 July 2006. The solid black line in the shape of 8 shows the nadir track of the two satellites. The two green dots show the satellite locations. The bottom satellite (SAT-1) is ascending while the top one (SAT-2) is descending. Note the overlap region uses a different color bar from the right. This is the time when SAT-1 starts to have full disk scan of the earth.

B. Two Tundra Satellites

NWS has expressed interest in the domain of longitudes from 180°W to 120°W and latitudes from 25°S to 75°N with 10-min imaging RR and IR footprint size better than 4 km (referred to as NWS domain). Such imaging capability is currently not available from either GEO or LEO. A constellation of two Tundra satellites can be used for such a regional application. To ensure the best coverage for regional applications, the Tundra satellite orbits need to be configured in such a way that both are optimal for the same region and the two satellites need to be separated by 12 h. This ensures that there is always at least one satellite focusing on the desired region all the time. To test that, the two satellites (SAT-1 and SAT-2 in Table II) optimized for the Alaskan region are used. The two orbits are configured similarly with RAAN and the mean anomaly difference of 180° (see Table II).

Fig. 4 shows the footprint size imagery of the two-satellite constellation with the inclination angle of 90° along with the nadir track at five UTC on 01 July 2006. The two satellites share the same classic 8-shape nadir track, which is symmetric along the longitude of 150°W, the longitude optimized for by both satellites. The nadir track has two sides, the north side and the south side. The two sides meet at the intersection of the 8-shape track at 30°N, 150°W. For this particular inclination angle, the two satellites meet at the intersection and they spend equal amounts of time on either side of the track. There is always one satellite on the north side, dwelling around the Alaskan region for 12 h. That is the region where this particular Tundra satellite is focused to observe. At this particular time, both satellites see the Alaskan region. And the resulting EFS is clearly better than 4 km for the region. Note that the Alaskan region could be seen even if the satellite is on the south side of the track, as shown in Fig. 4. These results indicate that the two-satellite constellation could be used for applications to the Alaskan region. However, it is not clear if this two-satellite constellation fully covers the NWS domain.

Fig. 5(a) shows EFS imagery for the domain with full temporal coverage (a 10-min RR) and EFS better than 4 km, from the constellation of two Tundra satellites

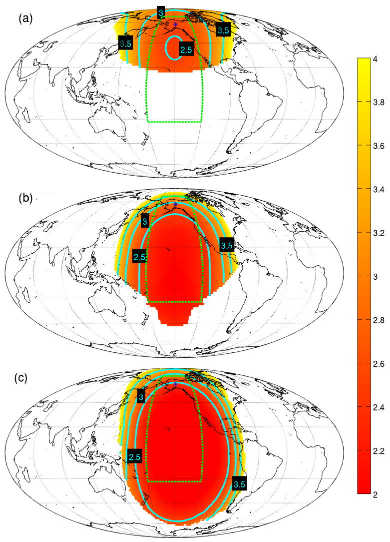


Fig. 5. Effective footprint size imagery (better than 4 km only) of the ABI/Tundra two-satellite constellation for area with full temporal coverage for the inclination angles of (a) 90°, (b) 45°, and (c) 63.4° plus ABI/GOES-17. The cyan contours show the EFS as well. And the green dash lines denote the NWS domain with requirements of full temporal coverage and footprint size better than 4 km. The horizontal black dashed lines denote the boundaries between polar regions, high latitudes, and mid-latitudes. The blue star shows the location of Fairbanks Alaska.

(SAT-1 and SAT-2 in Table II), optimized for the Alaskan region, with the inclination angles of 90°. This domain is relatively large, including the Alaskan region, the Arctic, much of the Contiguous United States (CONUS), northeast Asia, and the northern Pacific. The Alaskan region is not the area with the smallest EFS, but still better than 3.0 km. These results indicate that this constellation with the inclination angle of 90° can be used for regional application. However, it does not fully cover the NWS domain due to the large temporal gap in the tropics. This is because both satellites have the apogee at the North Pole. In order to increase the temporal coverage of the tropics, the inclination angle needs to be decreased.

To determine which inclination angle best covers the NWS domain, different angles are tested, including 63.4° (least secular precession of the perigee), 45°, 30°, and 15°. Results show that the coverage moves southward with a decreased inclination angle. In particular, at the inclination angle of 45° (SAT-3 and SAT-4 in Table II), Fig. 5(b) shows that the whole NWS domain (the green dashed area) is observed with full temporal coverage by the two-satellite Tundra constellation. Most of the NWS domain has an EFS better than 2.5 km (mostly the Pacific Ocean). The remainder of the NWS domain has EFS better than 3.5 km (mostly the Alaskan region). It is important to point out that other inclination angles do not fully cover the NWS domain. Angles larger than 45° result in a gap in the south of the NWS domain. And angles smaller than 45° result in a gap in the north of the NWS domain. This is consistent with the fact that the four corners of the NWS domain are close to the edge of the full temporal coverage.

Another option is to take advantage of existing observing systems, such as through a constellation of Tundra and GEO satellites. Since LEOs do not have needed temporal imaging capability, they are not considered. Fig. 5(c) shows the EFS imagery from the constellation of two Tundra satellites with the inclination angle of 63.4° and GOES-17. Compared with Fig. 5(a) and (b), this constellation results in a much larger area with full temporal coverage and EFS better than 4 km. This includes almost the whole Pacific, most of the CONUS, and northeast Asia. In the northern polar region, the Arctic is not fully covered because the apogee is located at the latitude of 63.4°N. In the southern polar region, the Antarctic is not covered because the Tundra satellites are not optimized for the region and GOES-17 does not have the coverage. Since GOES-17 is located at the longitude of 137.2°W, the coverage is skewed toward the east a bit in the southern mid- and high-latitudes. Within the large coverage by this constellation, most areas have an EFS better than 2.5 km between 60°S and 60°N. The outer area has coarser EFS, including the Alaskan region with an EFS still better than 3 km. A larger inclination angle (such as 90°) can further increase the coverage of the northern polar region, but may degrade the EFS in the tropics and mid-latitudes. These results indicate that a constellation of two Tundra and one GEO satellite can provide needed imaging capability for a relatively large domain with full temporal coverage and adequate footprint size. This constellation allows more versatility on the coverage in the polar region with different inclination angles for Tundra satellites.

C. Three Tundra Satellites

A multisatellite constellation is an effective way to fill the temporal and spatial gaps left by a single satellite. Depending on the applications, the orbital configurations need to be different. For regional applications, as demonstrated in previous sections, each satellite needs to be configured optimally for the same desired region. For global applications, though, the orbital configuration needs to follow a different strategy: avoid overlap as much as possible. This helps increase global coverage.

This section focuses on evaluating the imaging capability from a constellation of 3 satellites from Tundra, GEO, and LEO orbits. For GEO, the three satellites are evenly distributed around the Equator, with one at GOES-17 location, and the other two at 120° east or west of GOES-17. For LEO, the three satellites are separated by 4 h in Equator crossing time, with one in SNPP orbit. To help avoid spatial overlap in the polar region, the three satellites' polar passing time is separated by about 34 min. For Tundra, the three satellites' orbits (SAT-1, SAT-5, and SAT-6 in Table II) are shown in Fig. 6. They are evenly distributed in the argument of perigee: 30°, 150°, and 270°. All three satellites have the same inclination angle of 90°. Together with the same RAAN and the same mean anomaly, all three satellites are always evenly distributed in the same RAAN plane, separated by 120° with minimal overlap. For a three-satellite constellation, the MSA of 12° is used to ensure a full disk throughout the whole flight. Note that the MSA of 12° does not require more advanced sensing technology than what is currently available from the GOES-R ABI. However, more detectors might be needed to maintain the current coverage scan speed.

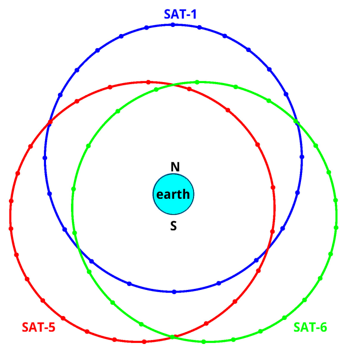


Fig. 6. Three Tundra orbits with the inclination angle of 90° with different arguments of perigee: 270° for SAT-1 in blue, 150° for SAT-5 in red, and 30° for SAT-6. They also have the same RAAN plane. The dots on the orbits represent the hourly interval of the full period of 24 h. Note that the hourly intervals near apogee appear shorter in distance than perigee, indicating longer dwell times near apogee, the most unique advantage of Tundra satellites.

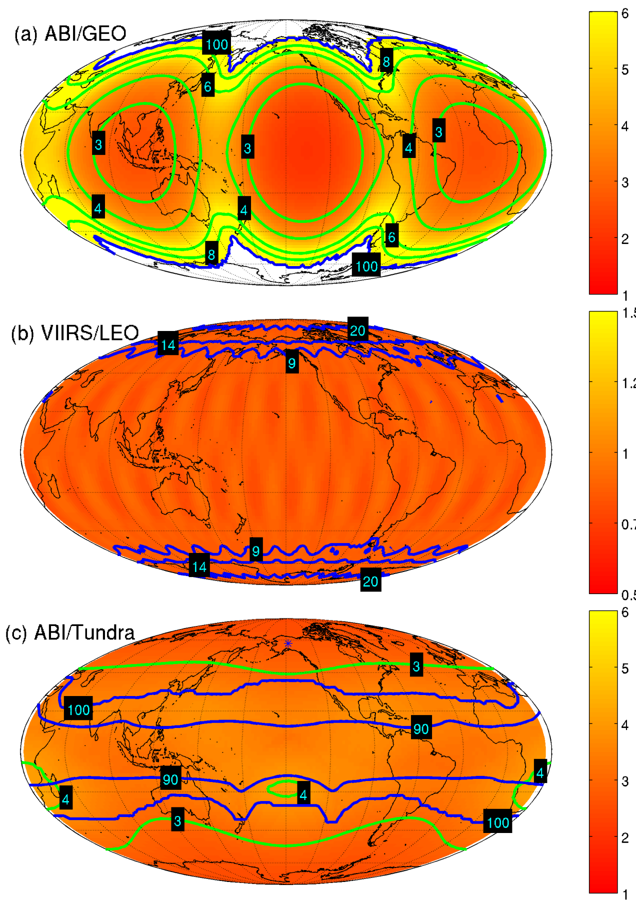


Fig. 7. Similar to Fig. 3 but for constellations of three satellites. The blue star in (c) shows the location of Fairbanks Alaska.

Fig. 7(a) shows that the constellation of 3 GEOs provides full temporal coverage of the tropics, the mid-latitudes, and much of the high latitudes. For this particular constellation, there are gaps in the polar regions and high latitudes around longitudes of 10°E, 130°E, and 110°W. More importantly, the EFS degrades rapidly with increased local zenith angle. Using the NWS need of 4 km as the standard, the GEO

TABLE III
REGIONAL COMPARISON OF CONSTELLATIONS OF DIFFERENT PLATFORMS. THESE ARE THE MEAN VALUES OF THE REGION FOR DATA CONTINUITY (DC) AND EFFECTIVE FOOTPRINT SIZE (EFS)

Region		**3 LEO**	**3 GEO**	**3 Tundra**	**3 Tundra+ 3 GEO**
Northern polar region	DC EFS	23 % 0.85 km	6 % 10.6 km	100 % 2.6 km	100 % 2.6 km
Northern high latitudes	DC EFS	9 % 0.85 km	85 % 6.4 km	100 % 2.8 km	100 % 2.6 km
Northern Mid-latitudes	DC EFS	6 % 0.85 km	100 % 3.8 km	99 % 3.4 km	100 % 2.5 km
Tropics	DC EFS	5 % 0.85 km	100 % 3.0 km	87 % 3.5 km	100 % 2.4 km
Southern Mid-latitudes	DC EFS	6 % 0.85 km	100 % 3.8 km	99 % 3.4 km	100 % 2.5 km
Southern High latitudes	DC EFS	9 % 0.85 km	85 % 6.4 km	100 % 2.8 km	100 % 2.6 km
Southern polar region	DC EFS	23 % 0.85 km	6 % 10.6 km	100 % 2.5 km	100 % 2.5 km

constellation's usefulness is limited to three relatively small regions in the tropics and mid-latitudes. There are gaps in polar regions and high-latitudes, as well as mid-latitudes and tropics in between the GEOs, where EFS is larger than 4 km. Fig. 7(b) shows that the constellation of three LEO cannot fill the gap left by the GEOs. Similar to the single satellite scenario, higher latitudes see more frequent observations than lower latitudes. The most frequently observed locations are at the poles with a DC of 30%, although the EFS (better than 1 km) is the best among the three platforms.

Fig. 7(c) shows that the constellation of three Tundra satellites, with the orbital configuration shown in Table II, provides full temporal coverage of the polar region and high latitudes in both hemispheres. The full temporal coverage extends down to the latitudes as low as 25°N or 25°S. The mid-latitudes in both hemispheres are slightly less frequently observed, but still more than 90%. The tropics are the least observed, with a minimum value of 74%. This is reasonable considering the arguments of perigee are placed for the North Pole and Southern high latitudes. In terms of the imaging quality, this constellation provides observations with EFS better than 3 km for the whole polar regions and most of the high latitudes. Using the NWS need of 4 km as the standard, most of the globe is satisfied except for a couple of spots in the southern hemisphere. These results indicate that the constellation of three Tundra satellites may be used to fill the gap left by GEOs by providing full temporal coverage of the polar regions and high latitudes.

Table III shows the comparison of the three constellations for different regions. The GEO constellation has full temporal coverage of the tropics and mid-latitudes. The temporal coverage for high latitudes is slightly reduced to 85%. Even the polar regions have limited temporal coverage of 6%. However, the mean EFS is degraded to 6.4 km for high latitudes and

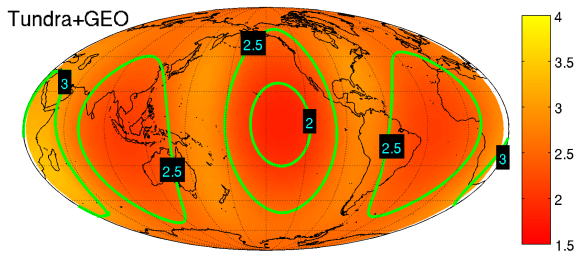


Fig. 8. Effective footprint size imagery of the constellation of three ABI/Tundra and three ABI/GEO for area with continuous observations (DCof one). The contours of (green lines) EFS are also shown.

10.6 km for polar regions, making it difficult to monitor small scale high impact events. As a comparison, the GEO constellation has an EFS better than 4 km in the tropics and mid-latitudes. The gaps in high latitudes and polar regions left by the GEO constellation, again, cannot be mitigated by the LEO constellation due to limited temporal coverage. Even at the polar regions, which are most frequently observed by LEOs, the mean DC is only 23%. The Tundra constellation, on the other hand, has full temporal coverage in polar regions and high latitudes, and almost full temporal coverage in mid-latitudes. The tropics are least observed but still have a mean temporal coverage of 87%. Unlike GEOs where EFS degrades rapidly toward the polar region, the Tundra constellation shows a little zonal variation in EFS. The tropics see the largest mean EFS of 3.5 km while the polar regions see the smallest of 2.6 km in the north and 2.5 km in the south. These results again show that the Tundra constellation provides unprecedented imaging capabilities in polar regions and much- improved imaging capabilities in high latitudes. It is complementary to the GEO constellation and can be used to fill the data gap left by GEOs.

Fig. 7 and Table III show that the Tundra constellation is useful in the high latitudes and polar regions, while the GEO constellation is useful in the tropics and mid-latitudes. It is, therefore, possible to use a constellation of three Tundra satellites and 3 GEOs to provide full temporal coverage globally with EFS better than 4 km. Fig. 8 shows that the whole globe has full temporal coverage by this constellation of 6 satellites and the EFS is better than 3 km for much of the globe. Compared with Fig. 7(a), all the gaps in between GEOs, high latitudes, and polar regions, are filled. The coarsest EFS is 3.4 km, better than the NWS need of 4 km. Table III confirms that all regions have full temporal coverage and mean EFS better than 2.6 km. These results show that the constellation of three Tundra satellites and 3 GEOs with careful orbital configurations can meet the NWS needs by providing global imaging capability with full temporal coverage and EFS better than 3.4 km.

These results do not mean the three Tundra + 3 GEO constellation can replace the existing baseline system of GEO satellites. Having more than 3 GEOs allows agencies/countries to provide their own contributions, develop their own capabilities, and obtain recognition with improved spatial resolutions over their sub-point locations. In the tropics and mid-latitudes, although redundant to GEO, Tundra satellites would make

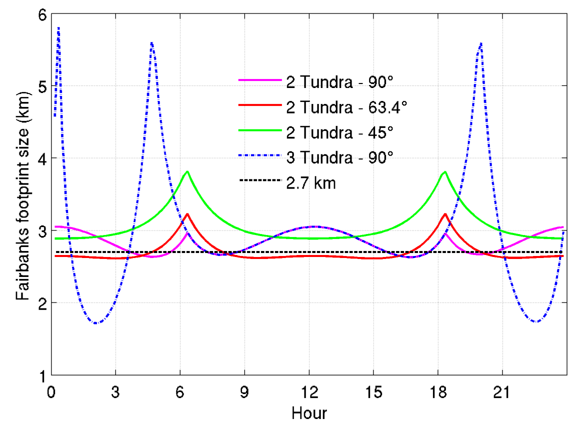


Fig. 9. Minimum footprint size of Fairbanks observed by different constellations. When there are multiple Tundra satellites observing the same location, the minimum footprint size is taken. Note that a segment is shared by the two Tundra with the inclination angle of 90° (magenta) and the two Tundra with the inclination angle of 90° (blue dash) from 6:20 to 18:20 UTC. The black dashed line shows the footprint size of 2.7 km.

the global space-based meteorological observing system more robust and resilient. They have the potential to maximize imaging capabilities to meet the global meteorological user requirements [21].

D. Footprint Size Comparison at Fairbanks

The smaller footprint size from the ABI/Tundra is critical for high impact events with small scales, such as forest fires. GEO fire detection suffers greatly with increased footprint size near the scan edge, i.e., the high latitudes [22]. Fig. 2(c) shows that one single ABI/Tundra will be able to provide high-quality monitoring of forest fires in Fairbanks with footprint size better than 3.05 km for 12 consecutive hours, as GEO does for tropical regions. Both Figs. 5 and 7 show EFS better than 3 km with full temporal coverage at Fairbanks. As pointed out before, DC and EFS provide no information on individual time steps. Thus it is not clear what the footprint size of individual time steps looks like for a constellation of multiple Tundra satellites. Specifically, it is not clear if those constellations can be used to monitor forest fires continuously.

Fig. 9 shows that all three constellations of two Tundra satellites are able to provide full temporal imagery observations of Fairbanks, with slightly variable footprint size, but better than 3.82 km, no matter what the inclination angles are. Each constellation has two segments. The segment from 6:20 to 18:20 UTC is from one satellite, while the rest of the time is from the other satellite. The two segments are identical to each other except that they are separated by 12 h. Out of the 24 h, the critical inclination angle (63.4°) provides a much longer time period (17.5 h), with footprint size better than 2.7 km, when compared with 6.5 hours from the inclination angles of 90° and 0 h from 45°. The inclination angle of 45°, since it focuses on the mid-latitudes, has an overall larger footprint size at Fairbanks than the other two.

The constellation of three Tundra satellites has three segments: 00:20 to 04:40 UTC, 04:40 to 20:00 UTC, and 20:00 to 00:20 UTC. The first and the third segments are from

SAT-5 and SAT-6 (see Table II). They are identical to each other but separated by 4 h and 20 min. They have shorter temporal coverage because both satellites have the argument of perigee in the Southern Hemisphere. The second segment is the longest one, from SAT-1. This constellation covers 21 h and 10 min out of 24 h with footprint size better than 4 km, and 8 h 40 min with footprint size better than 2.7 km. However, for the whole 24 h, the footprint size is better than 5.81 km, much better than GEO's footprint size of 8 km [Fig. 2(c)].

These results indicate that constellations of two Tundra satellites, via careful orbital configuration, are able to fill the data gap in Fairbanks left by GEO satellites. Those continuous, high quality, complementary imagery observations are critical to monitor high impact events such as forest fires. On the other hand, the specific constellation of three Tundra satellites, although with full temporal coverage, is less capable of forest fire monitoring with about 3 h having footprint size worse than 4 km. This is because the constellation is optimized for global applications. However, such imaging capability is still much better than that of GEO at high latitude.

V. Summary and Discussion

A Tundra orbit is one type of geosynchronous orbit that has a period of 24 h, just like the geostationary orbit. This allows the observation of the earth from high altitudes, a significant benefit to increase the spatial coverage. However, Tundra orbits are uniquely different from geostationary ones with nonzero eccentricity and nonzero inclination angle. The nonzero eccentricity allows longer dwell times near apogee than perigee. The nonzero inclination angle allows observing regions that are traditionally difficult to observe by geostationary satellites, such as high latitudes and polar regions.

To understand the advantages of Tundra orbits, tools were developed to simulate Tundra observations, including the orbit simulator, the navigation simulator, and the radiance simulator from high-resolution NWP model output. The simulation study shows that a single Tundra satellite may provide continuous observations of high latitudes such as Fairbanks Alaska for 12 consecutive hours with footprint sizes better than 3.05 km within a period of 24 h. Such imaging capability is not available from any existing observing system for Fairbanks.

The NWS needs satellite imagery observations with a RR of 10 min and an IR footprint size of 4 km or better for weather applications. Such imaging capability is only available from GEO satellites over tropics and mid-latitudes (referred to as GEO-like imaging capability). Two criteria are developed to quantify the overall imaging capability, including DC to characterize the temporal coverage and EFS to characterize the overall footprint size. This study investigates the imaging capability of Tundra orbits by putting an ABI-like instrument on Tundra satellites, in comparison to GEO and LEO, for both regional and global applications.

For regional applications, a constellation of two Tundra satellites, with both satellites focusing on the same region but separated by 12 h, can provide needed GEO-like imaging capability for a relatively large domain. The location of the domain changes with different inclination angles. It is found that two Tundra satellites with the inclination angle of 45° can meet the NWS needs of 10-min RR and footprint size better than 4 km for the domain of longitudes from 180° to 120°W and latitudes from 25°S to 75°N. The domain size can be further improved by taking advantage of existing observing systems, i.e., a constellation of two Tundra satellites with the inclination angle of 63.4° and one GEO.

For global applications, a constellation of three Tundra satellites, evenly distributed in the arguments of the perigee, can provide the needed GEO-like imaging capability for polar regions and high latitudes in both hemispheres. That represents unprecedented capability for polar regions and much-improved capability over GEO for high latitudes. While other regions do not have full temporal coverage, they still have a mean DC of 99% for mid-latitudes and 87% for tropics, adding robustness and resilience to the global space-based meteorological observing system. These results indicate that the Tundra satellites are complementary to GEOs and can be used to fill the data gap left by GEOs. This study shows that a constellation of three Tundra satellites and three GEOs can provide GEO-like imaging capability for the whole globe. However, having more than three GEOs allows for improved spatial resolutions over their sub-point locations, which could be more desired by individual agencies/countries. Having more than 3 GEOs also adds to the overall resiliency of the global system.

The two criteria, the EFS and DC, are useful to evaluate the overall imaging capability over a period of 24 h, or the period of Tundra satellites. That is not enough for some high impact events, such as forest fires, where continuous imagery observations with fine footprint size are desired. To understand the usefulness of constellations of multiple Tundra satellites for monitoring forest fires, the footprint size of Fairbanks Alaska is studied. Results show that the constellation of two Tundra satellites, optimized for the Alaskan region, can be used for monitoring forest fires. The constellation is able to provide continuous imagery observations with a footprint size better than 3.82 km. Specifically, the constellation with a critical inclination angle has 21 h and 10 min out of 24 h with footprint size better than 2.7 km. Such a small footprint size is critical to increase the fire detection rate and lower the false alarm rate. On the other hand, for monitoring fires at Fairbanks, the constellation of three Tundra satellites, optimized for global applications, is not as capable as the constellation of two Tundra satellites optimized for the Alaskan region. The three Tundra constellation provides imagery observations with footprint size better than 4 km for 21 h out of 24 h at Fairbanks. And the footprint size is as large as 5.81 km. But that is still much better than GOES-17's constant 8 km at this location.

While this study shows that Tundra satellites are complementary to the existing GEO and LEO observing systems, especially over the high latitudes and polar regions, some of the quantitative applications might be more challenging than those from GEO. For example, Atmospheric Motion Vectors (AMVs) are highly dependent on the accuracy of the satellite frame-to-frame co-registration and cloud height estimate. Being a geosynchronous orbit, Tundra is expected to achieve similar co-registration accuracy as GOES-R. The complications of Tundra's constantly changing satellite nadir location and altitude, as well as the calibration consistency between different Tundra satellites, might slightly degrade the co-registration. However, the Tundra AMV application will be invaluably complementary to GEO with finer footprint size and larger spatial coverage over the high latitudes and polar regions, and invaluably complementary to LEO with finer temporal resolution and larger spatial coverage over polar regions.

ACKNOWLEDGMENT

The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration's or U.S. Government's position, policy, or decision.

REFERENCES

[1] T. J. Schmit, M. M. Gunshor, W. P. Menzel, J. Li, S. Bachmeier, and J. J. Gurka, "Introducing the next-generation advanced baseline imager on GOES-R," *Bull. Amer. Meteorol. Soc.*, vol. 86, pp. 1079–1096, Aug. 2005, doi: 10.1175/BAMS-86-8-1079.

[2] W. J. Blackwell *et al.*, "An overview of the TROPICS NASA Earth venture mission," *Quart. J. Roy. Meteorol. Soc.*, vol. 144, no. S1, pp. 16–26, Nov. 2018, doi: 10.1002/qj.3290.

[3] *Vision for the Global Observing System (GOS) in 2025*, document WMO Rec. 6.1/1 (CBS-XIV), WMO, 2009, p. 7. [Online]. Available: http://www.wmo.int/pages/prog/www/OSY/WorkingStructure/documents/CBS-2009_Vision-GOS-2025.pdf

[4] L. Garand, J. Feng, S. Heilliette, Y. Rochon, and A. P. Trishchenko, "Assimilation of circumpolar wind vectors derived from highly elliptical orbit imagery: Impact assessment based on observing system simulation experiments," *J. Appl. Meteorol. Climatol.*, vol. 52, no. 8, pp. 1891–1908, Aug. 2013.

[5] R. Nassar *et al.*, "The atmospheric imaging mission for northern regions: AIM-North," *Can. J. Remote Sens.*, vol. 45, nos. 3–4, pp. 423–442, 2019, doi: 10.1080/07038992.2019.1643707.

[6] V. V. Asmus, V. A. Krovotyntsev, and V. P. Pyatkin, "Satellite monitoring of ice conditions in polar regions," *Pattern Recognit. Image Anal.*, vol. 22, no. 1, pp. 1–9, Mar. 2012.

[7] M. J. Bruno and H. J. Pernicka, "Tundra constellation design and stationkeeping," *J. Spacecraft Rockets*, vol. 42, no. 5, pp. 902–912, Sep. 2005.

[8] A. P. Trishchenko and L. Garand, "Spatial and temporal sampling of polar regions from two-satellite system on Molniya orbit," *J. Atmos. Ocean. Technol.*, vol. 28, no. 8, pp. 977–992, Aug. 2011.

[9] A. P. Trishchenko, L. Garand, and L. D. Trichtchenko, "Observing polar regions from space: Comparison between highly elliptical orbit and medium Earth orbit constellations," *J. Atmos. Ocean. Technol.*, vol. 36, no. 8, pp. 1605–1621, Aug. 2019, doi: 10.1175/JTECH-D-19-0030.1.

[10] S. Q. Kidder and T. H. V. Haar, "On the use of satellites in Molniya orbits for meteorological observation of middle and high latitudes," *J. Atmos. Ocean. Tech.*, vol. 7, no. 3, pp. 517–522, Jun. 1990, doi: 10.1175/1520-0426(1990)007<0517:OTUOSI>2.0.CO;2.

[11] A. P. Trishchenko, L. Garand, L. D. Trichtchenko, and L. V. Nikitina, "Multiple-apogee highly elliptical orbits for continuous meteorological imaging of polar regions: Challenging the classical 12-h Molniya orbit concept," *Bull. Amer. Meteorol. Soc.*, vol. 97, no. 1, pp. 19–24, Jan. 2016, doi: 10.1175/BAMS-D-14-00251.1.

[12] A. P. Trishchenko, L. Garand, and L. D. Trichtchenko, "Three-apogee 16-h highly elliptical orbit as optimal choice for continuous meteorological imaging of polar regions," *J. Atmos. Ocean. Technol.*, vol. 28, no. 11, pp. 1407–1422, Nov. 2011, doi: 10.1175/JTECH-D-11-00048.1.

[13] L. D. Trichtchenko, L. V. Nikitina, A. P. Trishchenko, and L. Garand, "Highly elliptical orbits for arctic observations: Assessment of ionizing radiation," *Adv. Space Res.*, vol. 54, no. 11, pp. 2398–2414, Dec. 2014, doi: 10.1016/j.asr.2014.09.012.

[14] A. P. Trishchenko, L. D. Trichtchenko, and L. Garand, "Highly elliptical orbits for polar regions with reduced total ionizing dose," *Adv. Space Res.*, vol. 63, no. 12, pp. 3761–3767, Jun. 2019, doi: 10.1016/j.asr.2019.04.005.

[15] K. S. Germain, F. W. Gallagher, and W. Maier, "Opportunities highlighted by the NSOSA study," in *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS)*, Jul. 2018, pp. 7387–7390, doi: 10.1109/IGARSS.2018.8517710.

[16] Z. Li, J. Li, P. Wang, A. Lim, J. Li, and T. J. Schmit, "Value-added impact of geostationary hyperspectral infrared sounders on local severe storm forecasts–via a quick regional OSSE," *Adv. Atmos. Sci.*, vol. 35, no. 10, pp. 1217–1230, 2018, doi: 10.1007/s00376-018-8036-3.

[17] Z. Li *et al.*, "The alternative of CubeSat-based advanced infrared and microwave sounders for high impact weather forecasting," *Atmos. Ocean. Sci. Lett.*, vol. 12, no. 2, pp. 80–90, Mar. 2019, doi: 10.1080/16742834.2019.1568816.

[18] S. Kalluri *et al.*, "From photons to pixels: Processing data from the advanced baseline imager," *Remote Sens.*, vol. 10, no. 2, p. 177, Jan. 2018.

[19] R. Gelaro *et al.*, "Evaluation of the 7-km GEOS-5 nature run," NASA Goddard Space Flight Center, Greenbelt, MD, USA, Tech. Rep. NASA/TM-2014-104606/VOL36, 2015, p. 285.

[20] Y. Chen, Y. Han, and F. Weng, "Comparison of two transmittance algorithms in the community radiative transfer model: Application to AVHRR," *J. Geophys. Res.*, vol. 117, 2012, Art. no. D06206, doi: 10.1029/2011JD016656.

[21] J. Schmetz and W. P. Menzel, "A look at the evolution of meteorological satellites: Advancing capabilities and meeting user requirements," *Weather, Climate, Soc.*, vol. 7, no. 4, pp. 309–320, Oct. 2015.

[22] J. V. Hall, R. Zhang, W. Schroeder, C. Huang, and L. Giglio, "Validation of GOES-16 ABI and MSG SEVIRI active fire products," *Int. J. Appl. Earth Observ. Geoinf.*, vol. 83, Nov. 2019, Art. no. 101928, doi: 10.1016/j.jag.2019.101928.

Zhenglong Li received the B.S and M.S. degrees in atmospheric sciences from Peking University, Beijing, China, in 2000 and 2003 respectively, and the Ph.D. degree in atmospheric sciences from the University of Wisconsin–Madison (UW), Madison, WI, USA, in 2009.

Since then, he has been a Research Scientist at the Space Science and Engineering Center, UW. He has more than 20 years of experience in meteorological satellite remote sensing, focusing on infrared sounders, both traditional and advanced hyperspectral. His research interests include retrieval algorithm development for atmospheric profiles and land surface emissivity, product validation and evaluation, application to weather forecast and nowcast, and observing system simulation study for future advanced satellites.

Timothy J. Schmit received the B.S. and M.S. degrees in meteorology from the University of Wisconsin, Madison, WI, USA in 1985 and 1987, respectively.

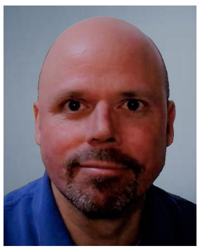
He is with the Advanced Satellite Products Branch (ASPB), National Oceanic and Atmospheric Administration (NOAA)'s NESDIS Center of Satellite Applications and Research, Madison, WI, USA. He has been recognized as an international expert in the field of geostationary remote sensing. With bachelors and masters degrees from the University of Wisconsin–Madison, he has dedicated his career to scientific support of multiple Geostationary Operational Environmental Satellites (GOES) missions and instruments, including the GOES-16/17 Advanced Baseline Imagers. His research interests span calibration, visualization, and algorithm development and he is committed to research-to-operations, training others and science communication.

Mr. Tim was awarded the Department of Commerce Gold Medal, National Weather Association T. Theodore Fujita Research Achievement Award, a 2018 finalist for the Samuel J. Heyman Service to America Award and was recently elected as a Fellow of the American Meteorological Society. He has authored or coauthored over 100 science articles in peer-reviewed journals, several book chapters, and co-edited a book, all associated with some aspect of GOES.

Jun Li received the B.S. degree in mathematics from Peking University, Beijing, China, in 1987, and the M.S. and Ph.D. degrees in atmospheric science from the Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China in 1990 and 1996, respectively.

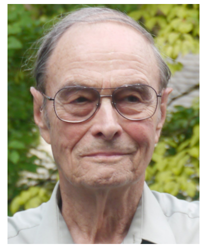
His research area includes retrieval of geophysical parameters from both geostationary and polar-orbiting satellite measurements, applications of satellite data in nowcasting, weather forecasting and numerical weather prediction (NWP), and future observing system simulation and impact assessment.

Dr. Li has authored and coauthored more than 200 peer-reviewed journal publications, and has been granted permanent principal investigator status, promoted to Distinguished Scientist, awarded the Chancellor's Award for Excellence in Research by University of Wisconsin–Madison.



Mathew M. Gunshor received his B.S.E degree in ocean engineering from Purdue University, West Lafayette, IN, USA, in 1993 and his M.S. degree in oceanography from Louisiana State University, Baton Rouge, LA, USA, in 1997.

He is a Research Scientist with the Cooperative Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin–Madison, Madison, WI, USA. His focus is on applied research projects in the areas of instrument design, algorithm development, data evaluation, training/user support, and identifying future needs. He has worked on ABI since 1999: band selection studies, algorithm development, waiver analyses, user training, post-launch tests, and transition to operations.



Frederick W. Nagle received the bachelor's degree in mathematics from American University, Washington DC, USA, in 1951. After serving three years as an Air Force pilot, he received the master's degree in meteorology from UCLA, Los Angeles, CA, USA, in 1958, and in 1967 a master's degree in mathematics from North Carolina State University, Raleigh, NC.

His first acquaintance with computers was a programming course on the SWAC computer at UCLA in 1955, which contained 256 words of random access memory. From 1958 to 1973 he was employed mostly by the Navy Weather Research Facility in Norfolk, Virginia. He joined NOAA/NESDIS in 1974, in Suitland, MA, and later in Madison, WI, retiring in 1994. From 1994 to 2020 he has worked part-time at the Space Science and Engineering Center (SSEC), University of Wisconsin, chiefly as a programmer dealing with collocation of satellite observations from different instruments and/or different satellites, and with the development of Meteorological Fortran (MeteFor), an enhanced version of the Fortran language designed with meteorological and spatial applications in mind.