Perturbation of Electromagnetic Radiation of Downlink in Orthogonal Components on the GOES 16 Satellite by Planar Antenna Phase Array

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Abstract. The Geostationary Operational Environmental Satellite - GOES 16 has an arrangement of planar antennas for uplink and downlink communications in the L-band range, UHF frequency (1694.3 / 1694.9 MHz), 16 W transmission power and a planar antenna array gain of 28 dBi, for communication operations and data scanning. The structure of antennas in the form of arrangement combines high directivity in the electromagnetic signal and reduction of the broadside, which corresponds to a smaller angular variation. Assuming a communication channel for the GOES 16, from the phase arrangement of planar antennas using 4 rectangular radiant elements of 30 cm x 30 cm (patch) in the transmission (downlink), we defined an expression for the gain of the array of planar antennas and model an acceleration for the satellite, due to the effect of the electromagnetic perturbation it admits, antenna theory and the energy-momentum conservation laws. For a state vector - 04/02/2019, at 18h 40m 12.44s, we implemented a routine using numerical methods with the equation of movement in the form of Cartesian components, which can be used for both keplerian movement as well as adding the desired disturbing accelerations. We propagate its orbit over a period of 5 days, with a step of 10 minutes, and correlate the results of this propagation in the propagated orbital model without disturbance and with the disturbance of the acceleration on the satellite of electromagnetic origin, centered in the phase arrangement of flat antennas. The perturbative effect of this model is applied on GOES 16 taking into account satellite mass, antenna characteristics, radiated power and maximum antenna gain. The numerical integrator used for the solution of the satellite motion equation is based on the fourth and fifth degree Runge-Kutta method, and the results shows that the phase arrangement of planar antennas with the described configuration implies a significant electromagnetic disturbance, changing the components in the direction (radial, transverse and normal) and the coordinates XYZ.

1. Introduction
Artificial satellites have well-defined orbits around the Earth. According to a more recent definition, the trajectory of a satellite can be a low orbit of 80 km up to 2.000 km from the Earth’s surface, a medium orbit between 2.000 - 35.786 km or a high earth orbit, over 35.786 km. For each orbit, the satellite supports specific functions and characteristics such as telecommunications (LEO – Low Earth Orbit,
below 2.000 km), Monitoring, Global Positioning (MEO – Medium Earth Orbit) and Geostationary and Remote Sensing (HEO – High Earth Orbit) (Montenbruck and Gill, 2005).

Satellite parameters can be seen as their state vectors can be perturbed by Moon and Sun (in the order of $5 \times 10^{-6}$ m/s$^2$), tidal forces (in order of $1 \times 10^{-9}$ m/s$^2$), direct solar radiation pressure (in the order of $1 \times 10^{-7}$ m/s$^2$) and atmospheric drag (less of $1 \times 10^{-9}$ m/s$^2$) (Montenbruck and Gill, 2005), (Teunissen and Montenbruck, 2017). The effects of this perturbations can be an increase of the major semi-axis, of the eccentricity, of the period, and changes in the other orbital elements, increasing inclination and the perigee argument (Montenbruck and Gill, 2005). Disturbances of electromagnetic origin were also presented magnitude order for acceleration over a satellite. Heilmann et al. (2012, 2013) consider that a satellite with a minimum weight of 1.000 kg, with a radiation of 100 watts from a parabolic antenna of communication, undergoes a perturbative acceleration of the order of $10^{-9}$ m/s$^2$, which cannot be neglected, because it corresponds to an order of 2 to 10% of the disturbance due to the solar radiation pressure (Cook, 1962).

When propagating the orbit of satellites considering the perturbations, are considered propagating models that are simulated by numerical methods (Cojocaru, 2007). With this method is possible to estimate with high precision and with the flexibility to include new perturbations, taking into account the influence due to each term of acceleration on a satellite (Gavish, 1997).

Satellites orbiting around the Earth do that by using the balance between centrifugal and gravitational forces and disturbing effects on their orbit, and a satellite must periodically correct its orbital elements in order to correct its orbits and trajectories (Eshagh and Najafi, 2007,). Considering that the downlink communication between the satellites and an antenna on the terrestrial surface is carried out from an antenna array, an electromagnetic disturbance model was implemented which considers a planar antenna array over a satellite with characteristics of the GOES 16 satellite, with the mass of 5.000 kg and 1.000 W EIRP transmission power and planar antenna array gain of 28 dBi. EIRP - Equivalent Isotropically Radiated Power is the product of transmitter power and the antenna gain in a given direction relative to an isotropic antenna of a radio transmitter ($EIRP = P_{rad} G$). Normally the EIRP is given in dBi, or decibels over isotropic. In the literature also the term effective isotropically radiated power is used.

2. Antenna arrays for satellite communication

Considering a flat surface on which the antenna elements, the square perimeter, are of uniform spacing between lines and columns of its elements, is possible to use the principle of multiplication of the diagram for a collinear set, in which the diagram of electric field of the similar set is the product of diagram of the isolated element by punctual isotropic amplitudes and phases relative to the original set (figure (1)) (Ippolito Jr, 1986). A high efficiency sub-array combined with a novel active global feed network is adopted in the receiving panel, while in the transmitting panel, a high efficiency sub-array is combined with a compact waveguide feed network. The configuration of the sub-array is based on a stacked microstrip patch antenna, in which a key feature is the microstrip feed network that assists to enhance gain and also has a vertical transition to allow the antenna to be integrated closely with RF components at the rear of the receiving panel (Stutzman & Thiele, 1998).

For an arrangement of antennas, the element of the set of diagrams $g_a$ is composed of an element factor, where the complete (normalized) diagram of an array of antennas is:

$$F(\theta, \phi) = g_a(\theta, \phi) f(\theta, \phi),$$

where $g_a(\theta; \phi)$ is the normalized diagram of an array of antennas (element diagram), $f(\theta; \phi)$ is the factor of normalized set.
Since the Poynting vector modulus is the ratio of the squared module of the electric field vector to the impedance in vacuum \( (Z_0 = 377\, \Omega) \), then:

\[
F(\theta, \phi) = \frac{S_{\text{rad}}}{P_{\text{rad}} / (4\pi r^2)}.
\]  
(2)

The angular directivity \( F(\theta, \phi) \) of an antenna is defined according to standard 145 - 1983 from the IEEE, in spherical coordinates and centered on the antenna, as the ratio between the intensity of radiation in a given direction \( S_{\text{rad}}(\theta, \phi) \) and the intensity of isotropically evaluated radiation (or mean radiation intensity) \( (P_{\text{rad}}) \), in all solid angles of a spherical region around the antenna (Heilmann et al., 2013).

From the antenna theory, it is possible to represent the power density radiated by an antenna such as:

\[
S_{\text{rad}} = \frac{G(\theta, \phi)P_{\text{rad}}}{4\pi r^2},
\]  
(3)

where \( G(\theta, \phi) \) is the ideal element gain, described in equation (3).

Considering yet the electromagnetic linear momentum conservation, and relating this electromagnetic momentum to an electromagnetic force, we include Newton's law to obtain an acceleration of electromagnetic origin.

From the antenna theory, by definition, \( EIRP = P_{\text{rad}} G \), then we consider that the total ideal element gain is normalized by a factor \( G \) such that \( G(\theta, \phi) = G(\theta, \phi) G \), as the gain in an antenna array does not change, but occurs in a single direction, in direction of connection with a receiving antenna in the terrestrial soil, this equation of the ideal gain is normalized by a factor \( G \). (Stutzman, 1998). We integrate the coordinates of the solid angle in the direction \( \hat{z} \). Thus we can rewrite the equation including in expression of acceleration:

\[
a_{\text{sat}} = -\frac{47.039EIRP}{c M_{\text{sat}}},
\]  
(4)

where the constant 47.039 has dimension of \([\text{kg m/s}]^{-1}\) and the velocity of light on vacuum is \( c = 3 \times 10^8 \text{ m/s} \). Thus the electromagnetic disturbance model for a planar antenna array \([\text{m/s}^2]\) is only function of the Equivalent Isotropically Radiated Power and satellite mass (Heilmann et al., 2012).

In the transmission protocol of the electromagnetic wave from the antenna arrangement of the GOES 16, the transmission time does not impact the results, since the model (equation 4) considers a continuous transmission of power, this means that, for these simulations, the GOES 16 downlink communication does not occur in pulses, but is performed continuously with an antenna installed on ground.
3. Interactive system of orbital parameters

As an integrator method will be used the Runge-Kutta method, which among other methods, is particularly easy to use and can be applied to different physical problems. To solve problems of ordinary differential equations, we will use numerical simulations which has the Runge-Kutta method, called ODE45 (Ordinary Differential Equation), propagated to a period of 120 hours, with a step of 10 minutes for integration and for absolute and relative tolerance of error, with a precision of $10^{-14}$ in the mantissa for position and velocity (Heilmann et al., 2012). We analyse the components of the electromagnetic acceleration from the satellite antenna reference in the Normal (N), Transverse (T) and Radial (R) directions to the orbit plane, respectively. The radiative force of the antenna is in the radial direction, so it occurs only for the radial component.

3.1 Parameters considered in the propagation of the orbit

The satellite orbit describes its position in the orbital plane at a given time $t$ and it is calculated using six orbital parameters, called orbital or Keplerian elements. These parameters describe the movement of a satellite around the Earth. The parameters are: major semi-axis ($a$) [m], eccentricity ($e$), slope of the orbital plane ($i$) [°], right ascension of the ascending node ($\Omega$) [°], argument of the perigee ($\omega$)[°] and mean anomaly ($M$). Where ($a$) and ($e$) describes the shape and size of the orbit described by the satellite; ($\Omega$), ($i$) and ($\omega$) are the Euler angles that define the location of the orbital plane in space.

The mass of the satellite is set at 5,000 kg with an Equivalent Isotropically Radiated Power – EIRP of the satellite antenna of 1.000 W. The GOES-16 satellite input parameters refers to February 04, 2019, at 18h 40m 12.44s.

For the model used in this work, parameters such as antenna gain, satellite mass and total radiated power from the satellite antenna are important for the correct modeling of disturbances in the satellite orbit. The value of the opening angle of the antenna is considered in the value of the maximum gain of the antenna of the satellite and, therefore, will be intrinsically considered in the calculations (figure 2).

![Figure 2. Parameter input screen of GOES-16 satellite.](image)

Because of the output of the program, we have a perspective of the orbit trajectory of the chosen satellite, and the possibility of constructing graphs that represent the behavior of its orbital elements.

4. Analysis of results

The orbit of the GOES-16 satellite was propagated to a time interval of 5 days with a step of 10 minutes, first with acceleration of the two bodies (reference orbit) and after this considering, the Electromagnetic
Reaction Acceleration Model (disturbed orbit). The results were then compared, between these orbits, by analyzing the positional deviations in the radial ($\Delta R$), normal ($\Delta N$) and transversal ($\Delta T$) components, according to the model. Considering the communication of the GOES-16 from a planar antenna phase array with 1.000 W of EIRP, it was observed that the velocity, major semi-axis, eccentricity, mean anomaly, longitude of ascending node, orbit slope, and argument of the perigee, did not suffer significant variations. However, the altitude of the GOES-16 suffered a maximum variation of 25 cm for the Y and 13 cm for the X coordinate of satellite. The components had values of 0.0 cm (Radial), 20 cm (Normal) and 0.0 cm (Transversal) (figure 2).

The acceleration of electromagnetic origin due to the communication of the GOES-16 satellite, using a planar antenna phase array with EIRP of 1.000 W, was $3.1382 \times 10^{-8}$ m/s$^2$. This acceleration needs to be considered in the orbit correction of the satellite, as it approaches the perturbative acceleration caused by solar radiation and albedo, both already considered in the orbit correction dynamics of the current satellites.

5. Conclusion
In this paper, we developed a model to describe the effects of radiation reaction in satellite orbits due to the emitted RF power by the satellite transmitting planar antenna array. We demonstrated that the satellite acceleration can be in the range of $\sim 10^{-8}$ m/s$^2$, which is similar to other small order effects that must be taken into account in order to correct the satellite trajectory. The perturbation caused by high gain antennas and/or high power transmitting systems are more pronounced that coming from small gain antennas, since the order of magnitude of the phenomena is directly proportional to the EIRP of planar antenna array. Therefore, an orbital correction of these coordinates of the GOES-16 satellite state vector is required.

6. References
[1] Gavish B 1997 Low Earth Orbit Based Communication System - Research Opportunities. European Journal of Operational Research 99(1) pp 166-179
[2] Cojocaru S 2007 A Numerical Approach to GPS Satellite Perturbed Orbit Computation. The Journal of Navigation 60 pp 483–495
[3] Cook G E 1962 Luni-Solar Perturbations of the Orbit of an Earth Satellite. Geophysical Journal of the Royal Astronomical Society vol 6 issue 3 pp 271–291
[4] Eshagh M Najafi Alamdari M 2007 Perturbations in Orbital Elements of a Low Earth Orbiting Satellite. Geodesy Department
[5] Heilmann A, Ferreira L D D and Dartora C A 2012 Perturbative Effects of Antenna Radiation Reaction on Artificial Satellite. Aerospace Science and Technology 23 pp 352–357
[6] Heilmann A, Ferreira L D D and Dartora C A 2013 Antenna Radiation Effects on the Orbits of GPS and INTELSAT satellites. Acta Astronautica 88 pp 1–7
[7] L J Ippolito Jr 1986 Radiowave Propagation in Satellite Communications. Springer
[8] Montenbruck O and Gill E 2005 Satellite Orbits: Models, Methods and Applications. Springer
[9] P J G Teunissen, O Montenbruck 2017 Springer Handbook Of Global Navigation Satellite Systems. Springer
[10] W L Stutzman, G A 1998 Antenna Theory and Design. 2nd Edition John Wiley & Sons New York pp 1-55