Modeling of Plasma Wave Generation by Orbiting Space Objects for Proximity Detection

Paul Bernhardt
Geophysical Institute Univ. of Alaska, Fairbanks, AK, USA
Lauchie Scott
DRDC Ottawa Research Centre, Ottawa, Canada
Andrew Howarth, Victoria Foss
University of Calgary, Calgary, Canada
George. J. Morales
Physics Department, University of California, Los Angeles, CA USA

ABSTRACT

Electromagnetic waves excited by satellites and space debris moving through the earth's plasma in low earth orbit can be detected in situ by a technique called Space Object Identification by Measurements of Orbit-Driven Waves (SOIMOW). Proximity measurements of space objects with plasma waves may allow tracking of space debris below the normal detection thresholds traditionally accomplished by optical telescopes and radar ranging sensors. SOIMOW uses in situ plasma receivers to identify space objects during orbital conjunctions. Satellites and other space objects moving through the near-earth ionosphere between 200 and 1000 km altitude become electrically charged by both electron collection and photo emission in sunlight. These hypersonic, charged objects excite a wide range of plasma waves. The SOIMOW technique has shown that electromagnetic plasma waves from known objects may be observed out to ranges of tens of kilometers, providing information on presence of the space objects. The SOIMOW concept has been demonstrated with the Radio Receiver Instrument (RRI) on the Swarm-E satellite. The amplitude, spectral, and polarization changes of the RRI data are consistent with electromagnetic, compressional Alfvén waves that are launched by charged space objects traveling across magnetic field lines. In addition, electrostatic waves at the space object can be generated by a lower hybrid drift or an ion acoustic wave instability. Both in situ electric field probes and remote detection of scattered satellite waves are being investigated to determine the location of orbiting objects.

1. INTRODUCTION

Objects, such as satellites or space debris, may generate plasma waves detectable by another satellite to determine their presence. All satellites in low earth orbit (LEO) pass through the F-Region ionosphere (Fig. 1). Ionospheric plasma waves generated by space debris can be used to protect spacecraft from collisional damage. Space debris consists of leftovers from human-made objects – such as discarded launch vehicles or parts of a spacecraft – typically trapped in orbit around the Earth. Currently, NASA tracks over 27,000 such objects in low Earth orbit. The European Space Agency (ESA) estimates that the total mass of all space debris in Earth's orbit is close to 22 million pounds (10 million kilograms). The number of debris that are too small to be tracked, yet large enough to cause severe damage upon impact, is in the millions. Since both space debris and active spacecraft travel at tremendous speeds of about 25,000 kilometers per hour, an impact of even a tiny piece of orbital debris with a spacecraft could create significant issues.

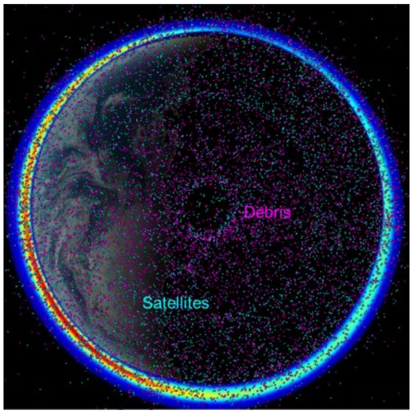

Fig. 1. Polar view of satellites and space debris in the SAMI3 model ionosphere

Traditionally, space debris are detected with satellite and ground sensors that use optics and ranging radars. These methods, however, cannot detect many smaller debris. Scientists from the University of Alaska and the University of Calgary have shown that space debris produces electric fields that surround them while in motion through the plasma in the ionosphere. Finding space objects with these waves, called Space Object identification by in situ Measurements of Orbit-Driven Waves (SOIMOW), relies on creation of plasma oscillations as charged space debris move through space. Both spacecraft and space debris become electrically charged as they are bombarded by solar photons and electrons from the plasma environment. Hypersonic charged objects can stimulate a wide range of plasma waves as they travel through the ionosphere, crossing the Earth's magnetic field lines.

2. OBSERVATIONS

Prior to conducting experiments to observe the waves generated by other satellites, measurements were made of plasma wave modes generated by the host satellite itself. The Swarm-E spacecraft (also known as CASSIOPE) was used for these observations. Archived data from the RRI electric field instrument have been analyzed to determine if the orbital motion of Swarm-E satellite body and booms could create plasma emissions. The spacecraft produces a VLF spectral feature called the Spontaneous Plasma Wave Emission (SPWE)[1]. Fig. 2 illustrates an examples of the SPWE near 15 to 20 kHz for satellite motion oblique to the magnetic field $\mathbf{B}_0$. These waves are observed above the local values of the ion cyclotron and lower hybrid frequencies. The data show frequency shifts, spectral spread, and intensity variations that may be related to changes in the object charging, background plasma density, and orbit direction. For the observed SPWE frequency ranges, the SPWE could be local (a) ion acoustic or (b) off-perpendicular lower hybrid waves. The self-generated plasma wave signal seems to intensify as the spacecraft charge becomes less negative. The spacecraft potential is derived from the IRM (Imaging Rapid Ion Mass spectrometer) particle instrument on Swarm-E by the University of Calgary. Both the RRI and the IRM are part of the e-POP suite of eight instruments. The SPWE is found in a frequency range that can correspond to whistler and ion acoustic waves for propagation along an oblique to the ambient magnetic field **B**. For propagation nearly perpendicular to **B**, these are finite-k_z lower hybrid waves[1].

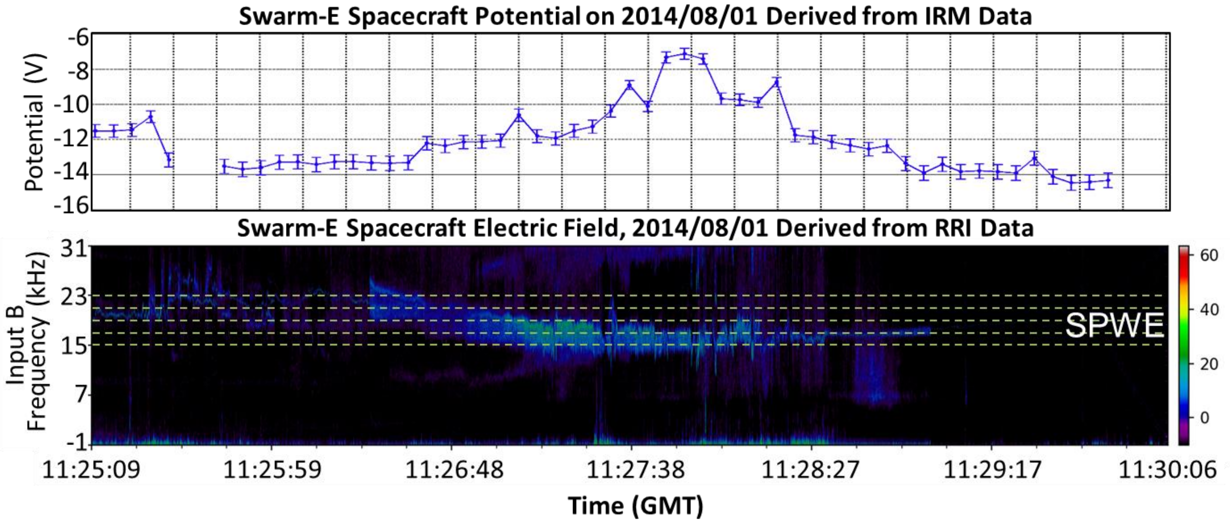

Fig. 2. Satellite plasma wave emission at VLF frequencies correlated with spacecraft charging.

The Radio Receiver Instrument (RRI) on the Canadian SWARM-E satellite has been attempting to detect plasma waves around orbital debris using electric field measurements at a point of interest (Fig. 2). The RRI observations seem to show magnetohydrodynamic (MHD) waves and electrostatic waves as far as 90 km away from the space object producing them. MHD waves are produced by crossing magnetic field lines which affect the motion of ions and electrons and the propagation direction of electromagnetic modes such as whistler, fast and slow magnetosonic, and Alfven waves. Electrostatic disturbances in the plasma are electric fields at the charged spacecraft and are not remotely detectable. The peak of this enhanced signal is found at the closest approach between the RRI detector and the target object. The cloud of enhanced plasma-wave noise lasts for about 20 seconds and is interpreted as spacecraft-driven turbulence comprised of a mixture of different kinds of plasma waves. Some observations of plasma wave disturbances associated with orbiting objects Starlink 2521, space debris from the COSMOS 2251 collision with Iridium 33, Iridium 911, and Starlink 2672 are displayed in Fig. 3.

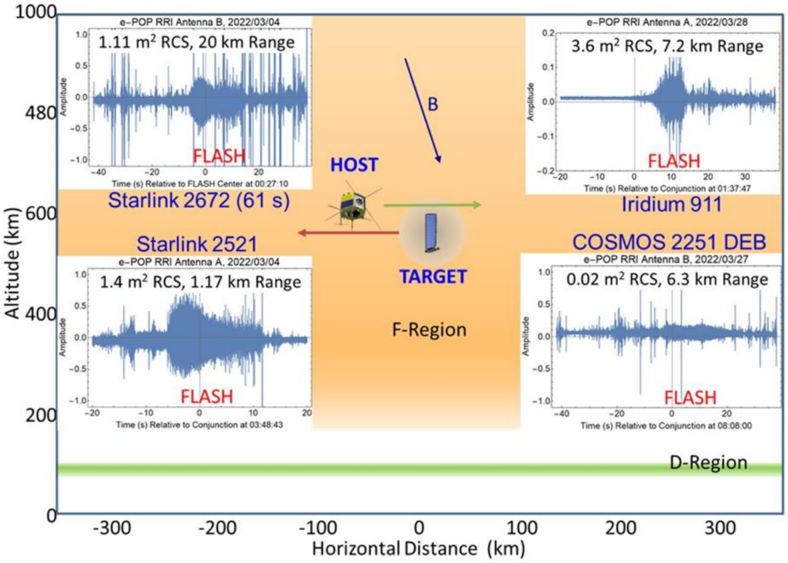

Fig. 3. Measurements of electric fields during *in situ* experiments by the Radio Receiver Instrument (RRI) on Swarm-E. Artificially enhanced plasma waves are labeled as a FLASH. The physical size of the orbiting targets is represented by their radar cross section (RCS). Minimum distance between the RRI host and target objects lies between 1 and 20 km.

All of the measurements show frequency spectra that range from below the ion cyclotron frequency to cutoffs at the local lower hybrid frequency as shown by the example in Fig. 4.

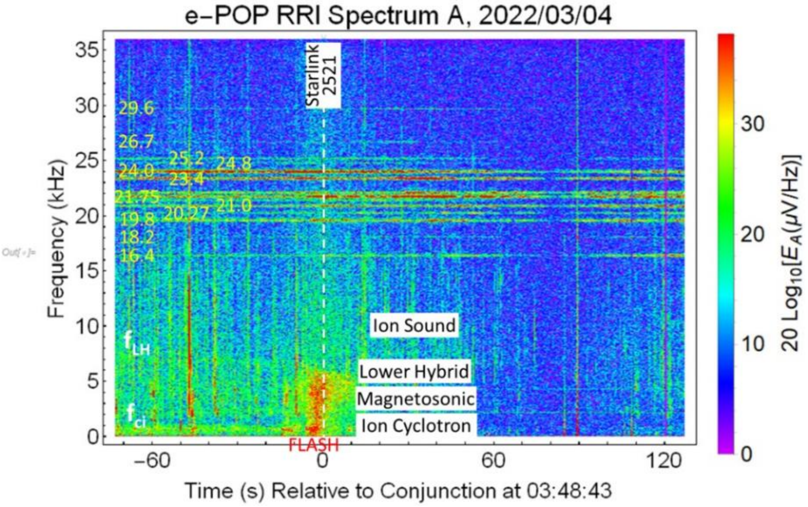

Fig. 4. Plasma wave spectrum the encounter of RRI with Starlink 2521. The spectra show background VLF transmitters at fixed frequencies, whistlers from lighting, and a large disturbance coincident with the passage of the satellite.

3. THEORETICAL INTERPRETATION OF DATA

Predictions for waves generated by orbiting space objects include (1) low magnetosonic and electrostatic ion cyclotron, (2) shear Alfvén, electromagnetic ion cyclotron, and ion acoustic, and (3) fast magnetosonic, whistler and electron cyclotron. Both linear disturbances and nonlinear solitons have been postulated in many papers [2].

Detection of space debris by plasma waves in space requires understanding of (1) the process for collection of electric charges on the debris, (2) the generation of waves produced by motion of a charged object in low earth orbit, and (3) remote sensing of the propagating electromagnetic waves or the non-propagating electrostatic waves generated by the moving object. These three process are shown by the block diagram of Fig. 5.

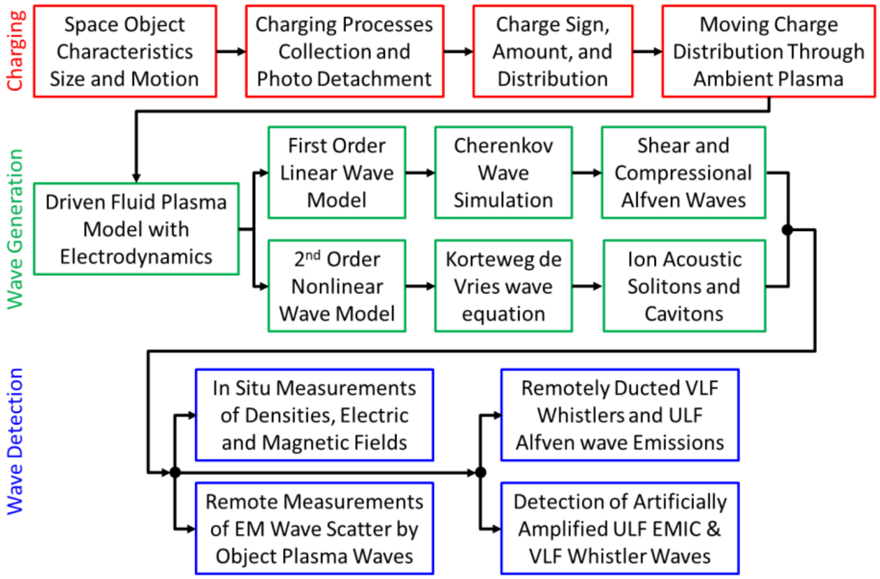

Fig. 5. Wave generation processes by charged objects in hypersonic orbits in the ionosphere

Detailed modeling is required for accurate spacecraft charging. The charge state of an object depends on photo emission of electrons by sunlight or electron collection by attachment of ambient electrons. Thus, precursor soliton production could be changed during the motion of the space object from darkness to sunlight across the Earth's terminator boundary or could be excited by a change in charge if the space object passes through an irregular electron structure in the ambient plasma. Rapid change between low-level and high-level negative charging that results from modest changes in the spacecraft charging conditions is essential to the generation of precursor solitons but is beyond the scope of this paper.

Consider a space object with charges that change in time. Temporal changes of electric charge on a spacecraft or space debris can drive both linear and nonlinear plasma waves to radiate in the reference frame of the object. Precursor solitons can be generated by an initial condition, a transient event, or a temporal fluctuations at the space object. These transient and temporal events could be a sudden change in electric charge, current, pressure, or neutral velocity.

To illustrate this temporal nature, the ion acoustic soliton model of is employed with considerations of the full range of nonlinear dynamics solutions to the Korteweg-de Vries Equation

$$\Phi(\xi,\tau)=N(\xi,\tau)=U(\xi,\tau), U_{ph}=1$$

$$\frac{\partial\Phi(\xi,\tau)}{\partial\tau}+\Phi(\xi,\tau)\frac{\partial\Phi(\xi,\tau)}{\partial\xi}+\frac{1}{2}\frac{\partial^3\Phi(\xi,\tau)}{\partial\xi^3}=\frac{1}{2}\frac{\partial S_2[\xi+(1-V_d)\tau]}{\partial\xi} \tag{1}$$

where ambient electron density, Debye length, ion acoustic speed, and electron thermal plasma potential

$$n_0, \lambda_D=\sqrt{\frac{\varepsilon_0 kT_e}{e^2 n_0}}, c_S=\sqrt{\frac{kT_e}{m_i}}, \omega_{pi}=\sqrt{\frac{e^2 n_0}{\varepsilon_0 m_i}}, \phi_e=\frac{kT_e}{e} \tag{2}$$

are used to normalize distance, time, electric potential, ion velocity, disturbed plasma density by

$$X=\frac{x}{\lambda_D}, T=\frac{c_s}{\lambda_D}t=\omega_{pi}t, \Phi(X,T)=\frac{\phi(x,t)}{\phi_e}, U(X,T)=\frac{u(x,t)}{c_S}, N(X,T)=\frac{n(x,t)}{n_0} \tag{3}$$

and the spatial coordinate is stretched by the ion acoustic phase speed with $\xi = X - U_{ph}T$ and $\tau = \omega_{pi}t = T$. The charge forcing function is the external object current in (1) divided by the object speed in the form a Gaussian function

$$S_2[\xi + (1 - V_d)\tau] = Ae^{-[\frac{\xi + (1 - V_d)\tau}{G}]^2}. \tag{4}$$

where G is the spatial size dimension and A is the charge. The forced KdV equation has been used by a number of authors. The important factors for these solutions are the magnitude and sign of the object charge A, the initial conditions for the charge source and the field disturbance at the start of the simulation, the size G of the charged object and the spatial boundary conditions. Previous work has displayed the results of simulations to show precursor ion acoustic solitons and trailing wake disturbances for positively charge objects. Those results are duplicated here with the additional emphasis of wake field transients and pinned oscillations for both positively and negatively charged spacecraft.

The normalized KdV equation (1) is solved numerically with Gaussian forcing (4) for periodic and absorption boundary conditions. The results are displayed in Fig. 6 in distance versus time coordinates to show (1) transient trailing fields triggered at the time of initial charging, (2) localized limit cycles near the object inside the source charged region, (3) cavitons trailing behind the object, and (4) precursor ion acoustic solitons launched at the forward boundary of the charged object by the limit cycle oscillations. Fig. 6 shows the potentials for both negatively and positively charged space objects in a spatial-temporal format. At the time of charging, transient solitons are launched in the wake of the object. Also in the wake is a region of negative potential expanding from the object which is either (a) uniform or (b) structured with cavitons depending on the charge sign. Near the object in the charged region, limit cycle oscillations are found with time periods that decrease with increasing charge. Precursor solitons are launched in the ram direction from the limit cycle oscillations.

It is well known that a spacecraft in the ionosphere is almost always charged negative unless an electron gun is used to remove electrons from the object[4]. Assuming positive charge for a negatively charged object may produce large errors in the orbit driven waves especially for the growth and detachment of precursor solitons. Previous theoretical work that use positively charged spacecraft should be examined for validity. The contrast of ion acoustic soliton generation for the sudden introduction of both positive and negative charges is presented here. The most important step for future research is self-consistent modeling of both object surface ionization to yield the correct excitation of electromagnetic plasma waves.

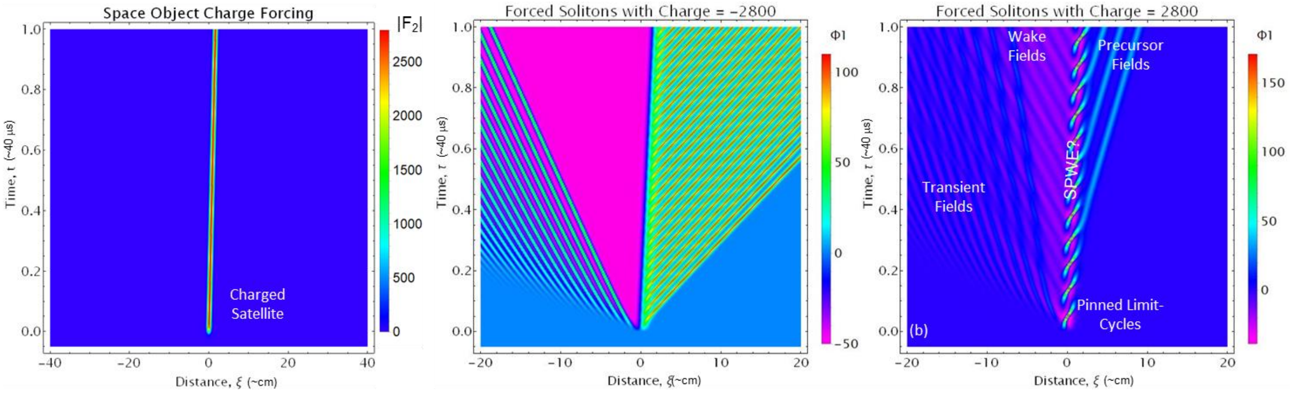

Fig. 6. Simulations driven by a transient electric potential (left) on an orbiting object that is (center) negatively or (right) positively charged starting at time τ = 0. Space objects will be negatively charged in the ionosphere and the center responses much more representative than that on the right.

Representative of models for plasma waves are derived from an initial boundary value problem solution to non-linear equations derived from plasma fluid equations or particle-in-cell (PIC) simulations. For precursor ion acoustic solitons, the nonlinear equation is derived from continuity, momentum, and Poisson's equation, where magnetic fields have been neglected. Magnetic fields cannot be neglected if the space objects is moving perpendicular to magnetic field lines because under those conditions, ion acoustic wave solutions do not exist below the local lower hybrid frequency. Nonlinear models that start with zero initial amplitude and have a sudden introduction of charge at t = 0 produce the precursor solitons that propagate away from the space debris. It is not surprising that if, at t = 0, the charge on the object suddenly changes, it can launch a trailing disturbance. This, however, will occur only once at a transition time for the space object and will not be repeated unless some other transient space event occurs.

For PIC simulations of slow and fast magnetosonic waves, the start-up scenario is a high-velocity ion beam instantly appearing at time t = 0 in the plasma. In both the ion acoustic and magnetosonic simulations, the precursor solitons are generated by the instantaneous appearance of the charged space object. In reality, spacecraft charging time is dependent on the charging process and is not instantaneous. Also, for precursor solitons to be useful, they must be sporadically regenerated as transient events in space. In steady state, charged space debris do not generate precursor solitons.

The SOIMOW observations shown in the previous section indicate that the waves may be a fast (or compressional) magnetosonic mode propagating quasi-perpendicular to the magnetic field lines where their frequencies are limited by oblique lower hybrid waves as illustrated by the linear dispersion curves (Fig. 7) where ion sound waves are only found about the lower hybrid frequency.

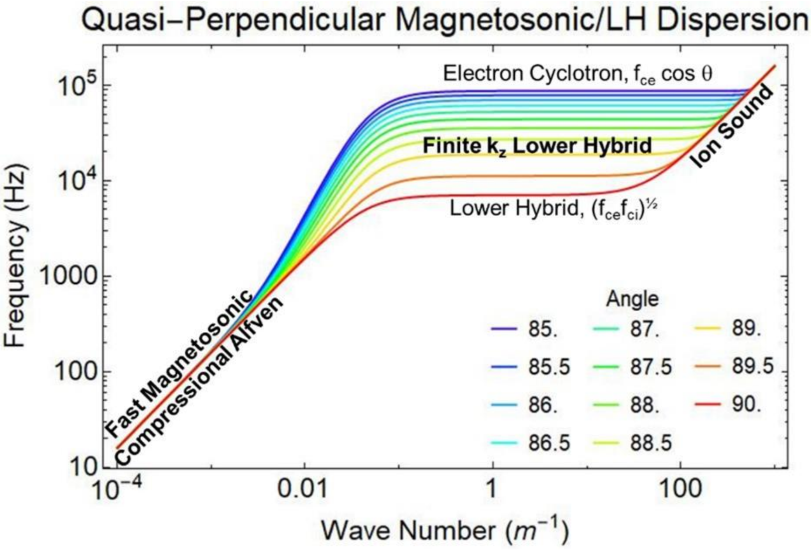

Fig. 7. Waves from satellite proximity conjunctions have the characteristics of transverse compressional Alfvén (TCA) and finite k_z lower hybrid (LH) waves with transitions to ion sound waves at the shortest wavelength. Dispersion for these curves assumes a warm plasma and that propagation at a propagation angle with $\mathbf{B}_0$ near 90^o.

Based on the SOIMOW observations of objects that travel much slower than the Alfvén speed, the spacecraft driven Alfvén waves must be linear disturbances with limited extension along magnetic field lines. The most plausible theory for generation of the linear waves is the Cherenkov mechanism. All the observations are consistent with the excitation of compressional Alfvén (fast magnetosonic) waves with their frequency limited by the local value of lower hybrid wave around 8 kHz in the ionosphere. Cherenkov radiation generated by charged spacecraft can propagate along, oblique, and transverse to the ambient magnetic field. For quasi-perpendicular motion, the integrated disturbance is computed along the coordinate transverse to both the satellite velocity x-direction and the magnetic field z-direction. This type of Cherenkov simulation to a 3-D Cartesian geometry with compressional Alfvén waves and whistlers will be explored in the future.

For now, shear (not compressional) Alfvén waves are considered in the inertial limit, where the Alfvén speed is much larger than the electron thermal speed of the plasma. These linear wave simulations have debris motion along orbit in one direction that provide a description of the resulting disturbance in both longitudinal and transverse directions [2]. Fig. 8a shows simulation results in the cylindrical geometry for the plasma wave of equation. The simulation parameters represent localized charged space debris moving through a background plasma along the magnetic field with the spatial-temporal evolution of the current density with a Gaussian cross section. When the charged space object travels perpendicular to the magnetic field, the range of the disturbances are extended to even larger distances (Fig. 8b). The large charge induced current at the spacecraft excites Alfvén Waves many kilometers along the magnetic field lines and trail behind for a few hundred meters. The out of plane (y-axis) disturbance also expands to a few hundred meters. Such an expanse of shear Alfvén waves is much easier to detect with an in-situ probe than those produced by orbital motion along magnetic field lines.

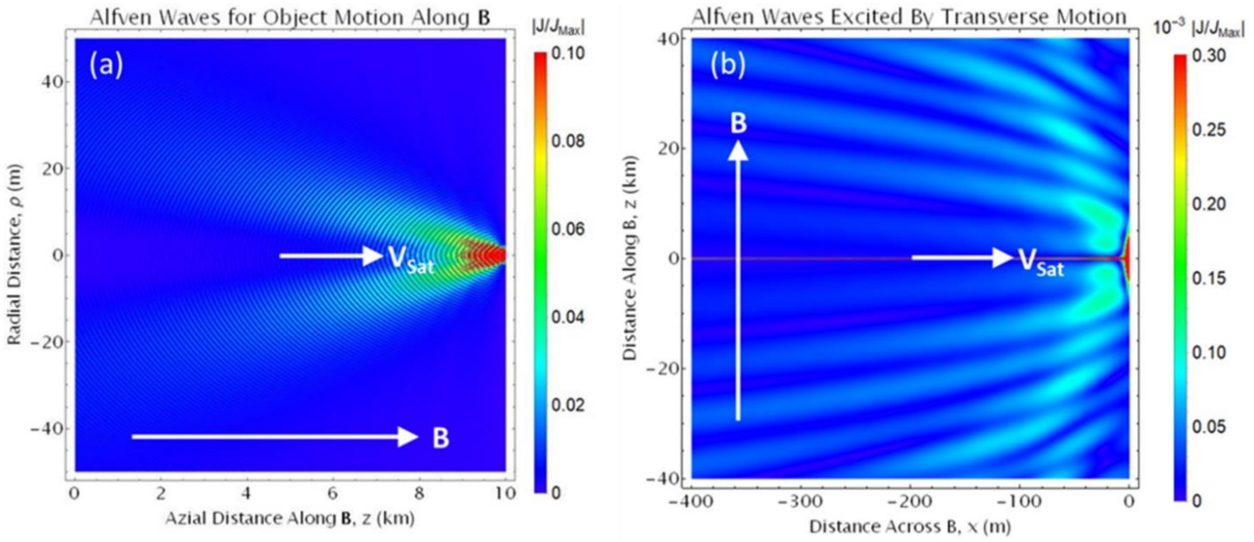

Fig. 8. Numerically simulated Cherenkov radiation for currents associated with shear Alfvén waves from the space debris in orbit (a) along and (b) across magnetic field lines. The charged space debris is at the point of maximum current along the orbit in both cases. Note the change in spatial scales between parts (a) and (b). The satellite is shifted in position to (a) z = 10 km and (b) z = 0 km.

4. SUMMARY AND CONCLUSIONS

Traditionally, space debris are detected with satellite and ground sensors that use optics and ranging radars. These methods, however, cannot detect many smaller debris. Scientists from the University of Alaska and the University of Calgary have demonstrated a novel technique for locating space debris by measuring the electric fields that surround them while in motion. This new technique, called Space Object Identification by in situ Measurements of Orbit-Driven Waves (SOIMOW), relies on creation of plasma oscillations as charged space debris move through space.

The Earth is surrounded by the ionosphere – a plasma layer with thermal ions and electrons. All satellites move through this plasma at speeds greater than the speed of sound. Both spacecraft and space debris become electrically charged as they are bombarded by solar photons and electrons from the plasma environment. Hypersonic charged objects can stimulate a wide range of plasma waves as they travel through the ionosphere, crossing the Earth's magnetic field lines.

The Radio Receiver Instrument (RRI) on the Canadian SWARM-E satellite has been attempting to detect plasma waves around orbital debris using direct measurements at a point of interest. The RRI observations seem to show magnetohydrodynamic (MHD) waves and electrostatic waves as far as 90 km away from the space object producing them. MHD waves are produced by “striking” magnetic field lines, much like plucking a guitar string. Electrostatic waves are disturbances in the plasma that are caused by oscillating charged particles. The peak of this enhanced signal is found at the closest approach between the RRI detector and the target object [2]. The cloud of enhanced plasma-wave noise lasts for about 20 seconds and is interpreted as spacecraft-driven turbulence comprised of a mixture of different kinds of plasma waves.

The challenge is to convert these newly discovered waves into EM modes that propagate long distances to be recorded by remote satellites or even on the Earth. Accurate determination of source locations would use the angular spread and time of arrival recorded from multiple receivers. Processed data may yield an image of the space debris traveling through the ionosphere.

ACKNOWLEDGMENTS

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