FLOATING BARE TETHER AS UPPER-ATMOSPHERE PROBE

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1.- Space Issue Addressed

This study purports to investigate whether a conductive tether left uninsulated and electrically floating in LEO could serve as effective electron beam source to produce artificial auroras. Standard e-beams emitted from satellites are marred by satellite-charging problems and have small cross-sections (radius about one electron-gyroradius at KeV energies), requiring ground observation made possible by a beam energy-flux two orders of magnitude greater than in the strongest natural auroras; this compensates for the thinness of the emitting layer but results in gross beam distortions by nonlinear plasma effects. In addition, the gross perturbations produced by the intense beam emission in the space plasma around the spacecraft affect emission itself, and the luminous glow arising from electron bombardment in the return current contaminates sensitive optical instruments.

Because of the large ion-to-electron mass ratio, an electrically floating tether is biased highly negative over most of its length by the motional electric field. Ions impacting with keV energies liberate secondary electrons that accelerate away through the 2D local bias, race down magnetic lines, and result in peak auroral emissions in the E-layer. Since no current flows at tether ends the e-beam is free of spacecraft charging problems. The beam is also free of plasma-interaction problems: its very large cross section (twice electron-gyroradius × tether length) results in energy flux over 10^3 times weaker than in standard beams. In addition, emission of such a weak flux has no significant effect on the local plasma, and takes place far from any instrument. Beyond auroral effects proper, observations along the beam, from a spacecraft carrying a floating bare-tether, might provide real-time mapping of E-layer neutral density, of interest in numerical simulations of the atmosphere lying below, and in orbit decay and reentry predictions.

2.- Tether System Design

The tether operates at night-time, with power supply and a Hollow Cathode (HC) off, for current to vanish at both tether ends. For an eastward moving S/C, electrons are collected above a zero-bias point very near the top; each ion collected below picks up an electron to leave as neutral, electrons thus leaking out at the (OML) ion-impact rate increased by secondary emission with yield proportional to bias. Because ion collection is slow, ohmic effects are weak, a floating tether being near equipotential.

With full bias proportional to tether length L, the OML ion current varies as $pL \times \sqrt{L}$, with perimeter $p \approx 2w$ for a thin tape of width w; the total emitted secondary current, gauging beam performance, varies as $wL^{3/2} \times L$. Beam flux and footprint at the E-layer vary as wL and $L \times \sqrt{L}$ respectively (electron gyroradius, being proportional to square root of energy, varies as $\sqrt{L}$ at the start of the race down the magnetic field). Width w should be large to reduce the probability of cuts by debris, which increases with mission duration, but small enough to allow the tape to collect current in the OML regime (w less than about 25 mm). Column-integrated (line-of-sight) emission rates roughly vary as $wL \times L$, greater energy allowing deeper penetration down the E-layer.

The electron current at night flows downwards throughout the tether, resulting in magnetic drag. Power and HC at the top would be on at daytime, to partially reverse the current and reboost the spacecraft once per orbit, making the tether an autonomous e-beam source. Above some zero-current point, electron current flows and increases upwards to leave at the HC, and produces thrust; conditions below that point are as at night, resulting in drag. The supply power must produce thrust enough to balance the night and day drag.

Drivers for tether material properties are density low and conductivity high, leading to use of aluminum. Whatever w and L, the mass of a tape can be reduced by making it thinner. There exists, however, an optimal thickness δ yielding minimum system mass, which, for limited mission times, is made of mass related to the power subsystem and remaining hardware mass. At large enough δ, hardware mass, which accounts for spacecraft, end-mass/deployer, and tether itself, and is just taken proportional to tether mass $\sim Lw\delta$, is clearly dominant. At small enough δ, mass of power-subsystem (HC/PPU/Solar Array, counting as low as 20 kg/kw) is dominant: a tape very thin and thus having a large ohmic resistance, requires a large solar array to push current through. Thrust power is proportional to *motional field* × *current* × L, scaling as $w\,L^{5/2}$ if ohmic effects do not reduce OML current ($\sim wL^{3/2}$). The power-subsystem/hardware mass ratio would then scale as $L^{3/2}/\delta$.

Ohmic effects on thrust are strong, however (effects on day drag are sensible too). Ohmic effects are gauged by the ratio between OML current ($\sim wL^{3/2}$) and short circuit current (*conductivity* × *motional field* × $w\delta$), which also scales as $L^{3/2}/\delta$. For $L = 20$ km and typical orbit day/night conditions, the minimum occurs at $\delta = 0.18$ mm. The power-subsystem/hardware mass ratio is then 1.7; the *efficiency* ≡ Magnetic thrust power / solar array power is about 0.17.

A tape of width 12 mm would have a mass 116.6 kg; for hardware mass 4 times as large, total mass would be 1256 kg. The electric power required would be 39.5 kw, supply voltage and current being 1.09kV and 35.5A respectively. Since minimum system mass, scaling as $wL^{5/2}$, increases fast with tether length, the range of design values for L is narrow (15-25 km) because column-integrated ionization rates (~ wL^2) decrease rapidly with tether length.

HC-expellant mass must be considered in the case of long enough missions. Consumption rate is very low, however. Mass-flow rate and electron current in a state-of-the-art HC allow ascribing a "specific impulse" to ED-tethers in LEO that is over 10^2 times greater than the specific impulse of an Ion Thruster. For our optimal auroral-probe tether, expellant mass would take 180 months to be as large as power subsystem mass.

During the night in orbit, the electrodynamic torque is extremely small (it can be made to vanish by a proper distribution of top and bottom masses) and the tether keeps very straight and vertical. Although the day torque cannot be made to vanish, it is small; the skip rope instability would take 10 years to develop. Deploying our metallic tape without a flexible leader would require keeping friction inside the deployer under well defined limits.

3.- Observations scheme

Each point in the tether emits monoenergetic secondary electrons, both electron energy and flux increasing linearly with distance h from the top. Beam half-width perpendicular to the tether varies as $\sqrt{h}$. With the electric potential shallow for some distance from the tether, e-beam electrons are near uniformly distributed in azimuth when reaching the undisturbed plasma; this results in a definite pitch-angle distribution involving the (dip) angle between magnetic line and horizontal plane.

As beam electrons move in helical paths down magnetic lines, they are scattered in elastic collisions with air molecules, which both affect the pitch distribution and reduce beam flux by width broadening due to diffusion across magnetic lines. Electrons also lose energy in inelastic ionization and excitation collisions, followed by prompt photon emission in case of *allowed* transitions. Electron energy at any altitude depends on the density profile above, the h value at emission, and the pitch angle; electrons at low pitch penetrate further down. Simple, opposite models for pitch evolution (distribution frozen in initial form and uniform distribution reached immediately after leaving the tether and kept afterwards) show somewhat similar results.

The pitch-averaged, volumetric ionization rate is proportional to beam flux, local density, and electron energy (through cross-section dependence). With beam thick 250m at most, dwell-time at any particular point is much less than buildup time for the electron population density to reach a steady state. However, excited states with prompt emission through *allowed* transitions do reach a steady-state, emission rates then being proportional to excitation rates. Since cross sections have similar energy dependence for all interactions, there exist simple approximate relations between emission and ionization rates for prominent spectral bands and lines, under some standard conditions.

Observations from the spacecraft (at about 300 km altitude to be close to F-layer maximum while keeping away from the ISS) involve 'column'-integrated emission rates along straight lines extending over the ionization region. Surface brightness as measured in Rayleigh units, at each small angle from the magnetic field, mix altitude/h-

value effects. As a result, the narrow emission footprint of the beam, which is tens of kilometers long and covers a line-of-sight range of about 6°, shows a peak in brightness that is about 10^2 R for prominent bands and lines. Footprint length is greater for a 45° dip, varying little over a large part of a middle-inclination orbit.

Observations will use CCD cameras, a refractive system being lighter, simpler and allowing a wider field of view than a reflective one. For easier alignment, the angular field-of-view could be twice the angle subtended by the emission footprint, or about 12°. It proves convenient to have a large number of pixels of large size on each side of the CCD detector; 10^3 30μm-pixels make for a detector side of 30 mm, a 12° field-of-view then requiring a focal length of 15 cm. One could easily tile 9 10mm x 10mm chips to get a detector of 30mm x 30mm.

Brightness of 30-100 R is well above background noise, and noise from present values of dark current prove completely negligible; critical noise arises from the CCD readout. To get a large signal-to-noise ratio, the number of photons incident on a pixel must be large, requiring large pixels but also an entrance aperture subtending a large solid angle at the detector, and a long exposure time, which is limited by satellite motion. For a 0.1s exposure (atmospheric emission being reasonable homogeneous over 750 m satellite displacements), a f-ratio as low as 1, a 30 μm pixel, and 0.5 optics transmission, brightness of 30-100 R yields 1-3 photons per pixel, or a charge packet of two electrons for present quantum efficiencies close to 100%. Though the image is narrow across the footprint, it still covers about 5 pixels, allowing use of a binning mode that sums photons gathered by nearby pixels across the image with no increase in readout noise, to yield a 10-electron packet; the S/N ratio is too low, however, even with recent techniques yielding sub-electron readout. A S/N ratio $\sim 10^2$ will require use of Image Intensifiers, which are complex and costly but achieve net signal gains of about 1000.

In a first simple scheme, the camera would operate on the 391.4 nm (or the 427.8 nm) spectral band to determine the N_2-density, and the 777.4 nm and 844.6 nm lines, with definite branching ratios, to determine O_2- and O-densities, using three interference filters controlled by hardware to switch rapidly from one wavelength to another. An alternative would be using three cameras, each with a single filter. A third possibility would use a grating for a spectral separation of the incoming radiation. The narrow footprint would allow non-overlapping images at different wavelengths, a dimension of the array providing spectral information and the other dimension spatial information.

The tomography problem is complex. Line-of-sight measurements are here taken from one location instead of combining information from several (ground) stations. Standard convolution algorithms do no apply to a nadir-scan, which is here the case; backscatter effects may be fully ignored, however. As unknowns we take density values at a number of altitudes equal to the number of pixels along one side of the CCD detector, each pixel corresponding to a line-of-sight. We use an iterative solution scheme, evaluating a $10^3 \times 10^3$ kernel matrix using density values at step m to determine densities at step $m + 1$.

For any reasonable density profile, the kernel is numerically singular; this is a result of broadening having flattened considerably the peak in brightness versus line-of-sight. A

(Singular-Value-Decomposition) regularization technique does allow to proceed with the inversion. Iteration, however, does not converge if the initial guess for the density profile differs substantially from the actual profile; this appears to be a result from the highly nonlinear dependence of the kernel on density. Tomographic inversion is then carried in two steps. A direct approximation to the actual density profile is obtained by fitting parameters in a model and using a *Direction Set* (*Powell*) technique. This estimate is then used as initial guess in the kernel, to start the iteration of the regularized inversion process.

4.- Alternative scenarios

The solar array could be used to feed power to an Ion thruster, which would then provide thrust. With typical (propulsive) *efficiency* $\eta_{IT} \sim 0.65$ and exhaust velocity $v_{exh} \sim 30$ km/s, the effective *efficiency* of the Ion Thruster would here be, $\eta_{IT} \times 2v_{orb}/ v_{exh} \approx 0.32$. For the optimal self-thrusting tape previously considered, system mass would be reduced through savings in the power subsystem mass due to an efficiency gain by a factor $0.32/0.17 \approx 1.88$; this gain would be somewhat lower both because the full tether would now exert day-drag, and because the Ion Thruster would be heavier than a HC. Use of a thinner tape could reduce hardware mass with no effect on the power subsystem, but incipient ohmic effects at night would reduce auroral effects too. Ion thrusters become comparatively less convenient the longer the mission because they consume (propellant) mass at a much faster rate than a HC. For an auroral-probe mission reaching beyond a few months, use of the tape-tether itself for day-thrust will always result in a system lighter than a system using an Ion Thruster.

Ground observation across the beam could provide, in principle, direct vertical resolution of the density profile, but the signal is weak (brightness ≈ 1 *R*) because the beam is thin and the flux is low; there are sources of light in the night sky that mask any $1R$ effect. One way to increase the signal-to-noise ratio would be pulsing a HC located at tether bottom to allow electrons to escape there, after being collected over the length of the tether. This requires, however, to locate a second HC and its subsystems at the bottom, away from the power source. Also, night drag would greatly increase during HC-on periods. Independently, and aside from transients related to the HC on/off operation, transients in the bias/current pulse travelling along the tether could affect the workings of the tether as an e-beam source. Modelling the tether as a transmission line with a (no-loss) phase velocity close to the light velocity, the time for a pulse to travel down the line (6×10^{-5} s, for $L = 20$ km) is comparable to the time response of ambient oxygen ions to changes in bias (a few times 10^{-5} s, for a 10^{5} cm^{-3} electron density). Again, with tether resistance ($\sim 250\ \Omega$) comparable to the (no-loss) line impedance, a pulse should be strongly attenuated as it travels down the line.

5.- Issues for Future Study

i) For p values of a few centimeters as allowed by the OML collection law, a 20 km round wire would be much heavier than a tape of the same length and cross-section perimeter, and thus emitting the same current of secondary electrons. However, a round wire with values of p scaled down and L scaled up appropriately, could present the same ohmic effects, and keep both total emitted current and tether mass, and thus system mass. The wire corresponding to the 20 km long, 12 mm wide, 0.18 mm thick tape, would be 43 km long, with a 0.57 mm radius. The tape would produce greater flux but weaker energies and a smaller E-layer footprint. A detailed analysis of observation tradeoffs (with full account of ohmic effects on day and night drag) between use of an optimal tape as considered in this study and its corresponding, properly scaled round-wire, would be worth carrying out.

ii) Use of a limited number of line-of-sights and altitudes, in order to reduce the calculational time, shows that convergence in the iteration requires estimated (initial) density values extremely close to the actual ones. This appears to be a result of crudely describing a profile that covers over two orders of magnitude by giving a small number of values. Use of 10^3 line-of-sights and altitudes while keeping the calculation as a reasonable task would require adopting a new calculational scheme. At every iteration, and setting side the additional complication of a pitch-angle quadrature, determining each one of the $10^3 \times 10^3$ elements in the kernel-matrix (corresponding to one altitude and one line-of-sight, and thus to one *h*-value at emission), required solving for the energy at the given altitude/*h*-value by a Newton's method iteration that involves a quadrature. A much simpler though less precise scheme would first readily determine energy in an altitude/*h*-value grid by choosing a set of *h*-values and carrying out direct, upwind integration up to an equal number of altitudes. Further numerical work is required to confirm convergence in the new scheme.