Feature

XIPS Keeps Satellites on Track

by John R. Beattie

Science-fiction writer Arthur C. Clarke originated the idea of the now-indispensable geosynchronous, Earth-orbiting communications satellite. In 1945, Clarke published a nonfiction article in which he noted that artificial satellites placed in orbit above the equator at an altitude of about 22,300 miles—where their period would equal the rotation period of Earth—would appear to remain stationary above one site on the planet. Thus, he said, such satellites could relay radio messages between widely spaced locations on the planet. Clarke's vision became reality with the launch of Syncom II in 1963.

> **Ion propulsion systems reduce the weight and cost of carrying chemical propellants**

Since then, more than 280 commercial communications satellites have been launched into geosynchronous Earth orbit (GEO); 185 satellites currently occupy this coveted space; and an estimated 438 new ones will be launched into GEO before the year 2010.

Typically, GEO satellites serve communications purposes. Signals are sent from a ground station to a satellite, where the signal is amplified using a power amplifier, and then the strengthened signal is retransmitted to another ground station. Traveling at the speed of light, the signal reaches its destination within about 240 ms. Because they operate at such high altitude, only three strategically placed GEO satellites are needed to achieve worldwide coverage.

Figure 1. Xenon ion propulsion subsystem thrusters.

The point-to-point link works well as long as GEO satellites remain stationary with respect to Earth-based transmitters and receivers. However, the gravitational fields of the sun and the moon perturb the satellites. As a result, their orbits become inclined with respect to the plane of Earth's equator and require periodic corrections.

Conventional propulsion

Until recently, GEO satellites used an on-board chemical-propulsion system to maintain the necessary orbital plane. This so-called north-south stationkeeping (NSSK) was accomplished by short firings of the chemical thrusters on a relatively infrequent cycle (about once every two weeks). Although this approach can effectively control the geosynchronous orbits of satellites, chemical thrusters have a relatively low specific impulse—a measure of the thrust produced by a given amount of propellant. This low specific impulse has required GEO satellites to carry about 450 to 600 kg of propellant to perform NSSK over the lifetime of a typical 15-year communications spacecraft.

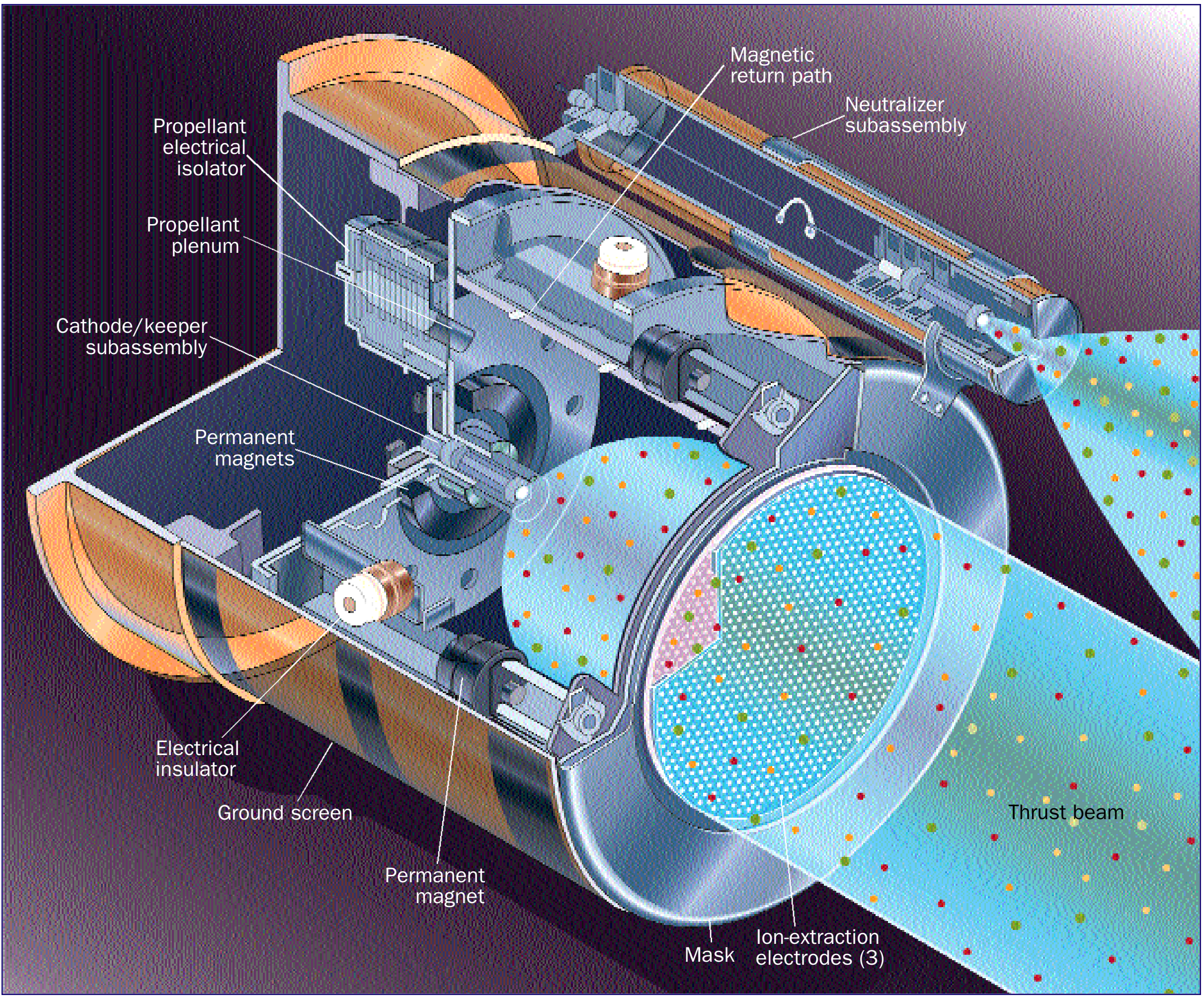
In addition to performing NSSK, chemical-propulsion systems are used both for east-west stationkeeping (EWSK) and to maintain satellite attitude control. EWSK compensates for a satellite's east-west drift, which is caused by Earth's oblateness. Spacecraft attitude control compensates primarily for the effects of solar radiation pressure. NSSK accounts for about 90% of the on-orbit chemical-propellant use; EWSK for about 6%; and attitude control for the remaining 4%. The current cost of delivering satellites to GEO averages about $30,000/kg, which makes the total cost of a typical communications satellite's propellants for stationkeeping and attitude control about $15 million to $20 million. Reducing propellant needs can save launch costs or increase the payload put into orbit for the same price.

Ion propulsion

During 1997, Hughes Space and Communications Company launched two commercial communications satellites equipped with a high-performance ion-propulsion system called XIPS (for Xenon Ion Propulsion Subsystem). This system produces about 18 mN of thrust at a specific impulse more than 8 times that of the typical chemical thrusters on GEO satellites, while consuming about 500 W of electrical power generated by the spacecraft's solar cells. The higher a system's specific impulse, the less fuel needed for a maneuver. The XIPS (pronounced "zips") propulsion system saves enough chemical propellant mass, nearly 400 kg, that a spacecraft can carry almost double the communications equipment of a traditional GEO satellite.

It may seem surprising, but the technology for such a revolutionary change in satellite propulsion has actually existed for years. The feasibility of ion propulsion was first demonstrated in laboratory experiments performed at NASA's Lewis Research Center in 1960, and the first flight demonstration of this technology took place in

1964. The reasons for the nearly four-decade gestation period include concerns about the early use of highly reactive cesium and toxic mercury as propellants, the limited power capacity available on satellites to operate ion-propulsion systems, the need to develop robust space batteries capable of thousands of charge/discharge cycles, and the reluctance to change from a proven technology to a new and unproved one.



Ian Worpole

Figure 2. Xenon gas is delivered to the thruster, ionized, accelerated, and neutralized.

How it works

A typical ion-propulsion system consists of a thruster (Figures 1 and 2), a power processor unit (PPU), and a propellant storage and control unit (PSCU). The PPU converts the spacecraft bus voltage into the regulated currents and voltages required by the thruster. Modern PPU designs contain all the internal logic required to start, safely operate, and stop the thruster, and they are controlled by on–off commands sent by the spacecraft-control processor.

A typical PSCU consists of a high-pressure storage tank, a pressure regulator, and various valves. Xenon gas is stored at an initial pressure of approximately 100 atm and is delivered to the thruster through a pressure regulator at a constant flow and pressure of 1 atm. A typical flow rate for a 500-W thruster is about 2.5 g/h.

The thruster consists of an ionization chamber, an ion-extraction assembly, and a neutralizer. Xenon gas atoms are supplied to the ionization chamber by the PSCU, where they are ionized by electrons emitted from a thermionic hollow cathode. The cathode consists of a refractory metal tube with a flow-limiting orifice and a porous tungsten cylinder impregnated with a barium-oxygen compound positioned immediately adjacent to the orifice. The cathode is brought to thermionic-emission temperature (approximately 1,100° C) using a coaxial heater positioned on the outside of the tube. Barium-oxygen-tungsten dipoles form on the hot cylinder, creating a low-work-function surface that produces electrons at a relatively low temperature, which reduces the amount of cathode-heating power needed. This surface emits an electron current density of about 1 A/cm^2.

During operation of the cathode, a larger number of electrons flow to the anode of the ionization chamber, and in the process, they ionize the xenon gas atoms by electron bombardment. However, a magnetic field produced by an array of permanent magnets prevents the electrons from traveling directly to the anode. Instead, the electrons spiral around the field lines and work their way to the anode by colliding with the gas atoms. During typical operation, the plasma density within the ionization chamber is low—about 10^{11} ions and electrons per cm^3, and the xenon density is about 10^{12} atoms per cm^3. Such ionization chambers are quite efficient; of the total power provided to the thruster, typically 70% is converted to ion-beam power (thrust power).

Ion extraction and acceleration

The ion-extraction assembly consists of three grids, each equipped with several thousand precisely matched apertures. The inner grid forms the downstream boundary of the ionization chamber and is typically several hundred volts positive of the spacecraft. The voltage applied to this grid determines the final velocity of the ions as they exit the thruster, which is directly related to the thrust and specific impulse.

The ions arriving at the inner grid are accelerated by the negative potential of the intermediate grid, whose

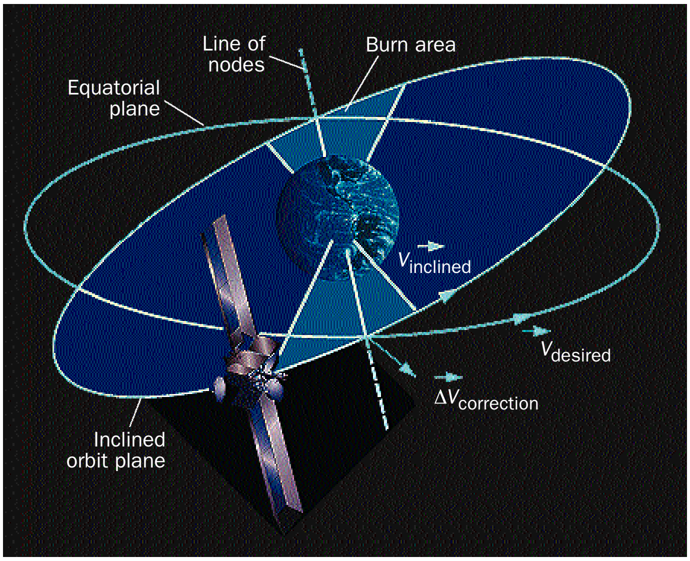


Figure 3. The sun and moon tend to increase the inclination of a satellite's orbit. Periodic thrusting near the line of nodes keeps the spacecraft in the equatorial plane.

voltage is about 25% of that of the positive grid. This produces a focused ion beamlet accelerated from each of the several thousand apertures. The negative potential of the intermediate grid also prevents electrons in the ion-beam plasma from backstreaming through its apertures. The outer grid is typically biased a few volts negative of the spacecraft. Its use is optional, but allows flexibility in thruster operation.

Ion-beam neutralization

The ion-beam neutralizer consists of a hollow-cathode electron source that is positioned outside of the beam of positively charged xenon ions. The neutralizer provides the necessary electron emission to both charge- and current-neutralize the positive ion beam. Current neutralization prevents the spacecraft from charging negative because of the ejection of positive charge in the ion beam. Charge neutralization prevents excessive beam divergence due to the mutual repulsion of charges of like sign. Ion-beam neutralization was such an important issue in the early development of ion propulsion that the first U.S. flight test of an ion thruster, which took place in 1964, was dedicated to demonstrating that ion beams could, in fact, be neutralized in space.

Ion-powered satellites today

A typical ion-propulsion system on a GEO satellite today includes two fully redundant string arrangements, each consisting of two thrusters and one PPU, for use in NSSK. EWSK is carried out by chemical thrusters.

NSSK is accomplished by firing a north thruster daily for a period of approximately 5 hours, with each "burn" centered on the time when the satellite, ascending in its inclined orbit, passes through Earth's equatorial plane (Figure 3). Twelve hours later, the south thruster is fired for the same duration, with the burn centered on the time when the satellite's descending orbital path carries it through the equatorial plane. Because the thrusters are typically aimed away from Earth, their firing introduces a radial component of thrust, which would normally cause an undesirable eccentricity in the orbit. However, this twice-a-day thrusting strategy automatically removes the eccentricity in any 24-hour period. The propulsive maneuvers are directed by the spacecraft's computer, which follows program commands uploaded to the satellite every two weeks.

Later this year, Hughes will launch a communications satellite equipped with 25-cm-diam XIPS thrusters that operate with an input power of 4,200 W to produce 165 mN of thrust, 9 times that of the XIPS systems launched in 1997. This will be the first GEO satellite to use an all-electric propulsion system. The XIPS system will perform all on-station maneuvers, including NSSK, EWSK, attitude control, and momentum dumping. In addition, the high-thrust XIPS system can be used to boost the 7,850-mile perigee of the satellite's initial elliptical orbit. Raising the craft to its 24-hour circular orbit at GEO will take up to 90 days, depending on the desired spacecraft-mass savings, and the use of XIPS will save as much as 450 kg of chemical propellant.

Other future applications of ion propulsion include planetary exploration. NASA, which has supported much of the industrial and university development of ion-propulsion technology, will launch its Deep Space 1 (DS-1) spacecraft later this summer. DS-1 is part of the Jet Propulsion Laboratory's New Millennium Program aimed at low-cost space exploration. The DS-1 spacecraft will utilize a 30-cm-diam xenon-ion thruster and PPU built by Hughes Electron Dynamics Division for NASA's Lewis Research Center. DS-1 will be launched into Earth orbit by a Delta II rocket, and then its ion-propulsion system will drive it to distant encounters with a comet and one or two asteroids. The DS-1 mission will qualify NASA's NSTAR ion-propulsion system for use in future New Millennium endeavors, including the DS-4/Champollion mission. DS-4 is designed to make the first landing of scientific instruments on the surface of a cometary nucleus.

In the future, we may also see ion-propulsion systems used in low Earth orbit (LEO). Large numbers of satellites are needed to relay signals transmitted from one point on the ground to another via a chain of satellites. Because of the low altitudes, these satellites transmit signals from satellite to satellite to achieve global coverage.

In this LEO application, ion propulsion could be used to transfer the satellites from their launch vehicle drop-off altitude up to their final operational altitude and then to maintain them in this orbit. At the end of their useful life, the ion-propulsion system could be used for deorbiting the satellites so that they eventually burn up harmlessly in the atmosphere.

BIOGRAPHY

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