I was appalled by the article **Big benefits from tiny technologies** in the October 1996 issue (p. 38). Have the writers stopped to think about the implications of "thousands of satellite constellations orbiting, for example, at 700 km altitude"? For a long time I have been worried about such projects as Iridium, which only proposed 77 (though now I see it's 161!). And as for Teledesic...words fail me.

I have already suggested that future space travelers may have to pass through orbiting mine fields. Now what's suggested is even worse—orbiting dust storms!

Although I am understandably biased in favor of geostationary satellites, I feel that the benefits of LEO satellites are exaggerated. They have no power advantage over GEO satellites, if spot beams are employed, and their one undoubted superiority is in the reduced time delay. If space travel develops as we all hope it will, they may have to be banned in the next century, as a hazard to navigation.

For the ultimate solution, see "3001: The Final Odyssey!"

Arthur C. Clarke
Sri Lanka

It is a memorable experience for us that articles we published (September and October 1996) have stimulated a letter from Arthur C. Clarke and given us an opportunity for this dialog.

Clarke has registered strong, prophetic concerns about future problems posed by the accumulation of long-lived debris in LEO. We discuss constellations of hundreds, or even thousands, of nanosatellites. He asks if we have considered "the implications of thousands of satellites orbiting...?" Of course we have.

In his new book, Clarke paints a society residing in space towers reaching from Earth to GEO and beyond and connected by habitat rings at uniform gravity. Poole, a time-travel visitor, asks his guide, Indra: "There were already thousands of satellites, at all sorts of altitudes, in my time. How do you avoid collisions?" She replies: "I believe there was a big cleanup operation, centuries ago. There just aren't any satellites, below stationary orbit."

Poole asks: "And there have never been any accidents—any collisions with spaceships leaving earth, or reentering the atmosphere?" She replies, "But they don't anymore. All the spaceports are where they should be—up there, on the outer ring. I believe it's 400 years since the last rocket lifted off from the surface of the earth."

Collisions with space debris are not hypothetical. They have occurred, for example by deliberate intent—as with the space mine explosions and other experiments in the early days of military satellite development, such as ASAT; and by accident—as when an

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orbiting paint flake chipped a Shuttle window, and when the Cerise satellite was disabled by collision with a piece of an Ariane booster. So this is clearly no longer an academic question. The orbiting dust storms feared by Clarke are already there, and are likely to grow substantially before the "big cleanup operation" noted by Indra is implemented in the 26th century.

At present we are tracking some 8,000 human-made space objects, but are still discharging effluent and debris into space with, as aptly stated by one colleague, all the abandon of an 1880 mining operation. The consequences are already impacting astronomical and space science operations.

Every spacecraft leaves a collateral trail of debris and spent upper stages. Under the action of solar fluctuations, atomic oxygen, and other subtle factors, these remnants have mysteriously exploded, spewing a legacy of hundreds of smaller fragments that could be the death warrant of a satellite or launch vehicle.

Nevertheless the pace increases, with over 70 metric tons of mass being placed in orbit each year. At present the debris risks are less than other risks of launch and space operations. A perhaps more ominous phenomenon is the incredibly violent explosions, with megaton energy releases, occurring in the upper atmosphere as a result of large meteorite entry. Over extremely long periods of time the natural threat will likely dwarf the artificial one.

The impact of space debris boils down to current cost and near-term costs. Insurance protects the commercial satellite investor, at a tolerable cost. Neither Iridium nor Globalstar considers debris to be a serious threat to its satellites. The odds of large objects running into each other is still small. However, a catastrophic accident might result in heightened legal and commercial consequences, and breakup of a satellite can have a domino effect on others in the same constellation. Near-Earth space is becoming a highly competitive, hot commercial property, and the legal aspects of space objects and pollution will become dominating in the near future.

There may also be other, more subtle effects of space debris and pollution that could affect Earth's inhabitants. In contrast to commercial satellites, space science and other government missions are financially exposed, and have already a far stronger incentive to address space debris.

Government planners for future space systems have already identified space debris as a threat to assets, and will be initiating activities to address the problem and the cleanup options. How solutions will evolve is at present unclear, but perhaps we need to impose the same discipline on space operations that terrestrial polluters face: environmental impact reports, waste disposal and mitigation plans, imposed cost for environmental dumping. For example, spent satellites could be deorbited; older satellites could be refurbished in orbit or retrieved and recycled. These remedies could be extended to satellites in higher orbits via reusable orbit transfer vehicles. Perhaps we need the robot orbiting equivalent of a dump truck.

Of course the issue of space debris was a well-recognized item in the evolution of our concept for distributed, mass produced nanosatellite constellations. In one conception the nanosatellite constellation is in LEO, where decay will occur in 1-3 years. Advances in microtechnology, MEMS, and quantum electronics will allow a massive data processing capability, in producible small integrated packages, with enough brains to preserve the constellation functions even as gradual decay is occurring. The short orbital life, vs. 15-year current targets, enables lower cost commercial electronics, and our work in micropropulsion enables a practical, affordable powered deorbit option. The small size enables novel launch concepts that are less polluting and do not suffer the devastating costs of a large space rocket and satellite failure. And of course the collateral debris is greatly reduced and decays relatively quickly from the low orbits, without any large fragments that can reenter and reach the Earth's sur

Even at higher LEO altitud required cleanup campaign w easier than at more distant rings, and nanosats that are not bited will be relatively simple cover for disposal.

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