D. Satellite Design

The GPS satellites are attitude stabilized on all three axes and use solar panels for basic power (see Fig. 6). The ranging signal is radiated through a shaped beam antenna—by enhancing the received power at the limbs of the Earth, compensation is made for "space loss." The user, therefore, receives fairly constant power for all local elevation angles.* The satellite design is generally doubly or triply redundant, and the Phase I satellites demonstrated average lifetimes in excess of 5 years (and in some cases over 12).

E. Satellite Autonomy: Atomic Clocks

A key feature of the GPS design is that the satellites need not be continuously monitored and controlled. To achieve this autonomy, the satellites must be predictable in four dimensions: three of *position* and one of *time*. Predictability, in the orbital *position*, is aided because the high-altitude orbits are virtually unaffected by atmospheric drag. Many other factors which affect orbital position must also be considered. For example, variations in geopotential, solar pressure, and outgassing can all have significant effects.

When GPS was conceived, it was recognized that the most difficult technology problem facing the developers was probably the need to fly accurate timing

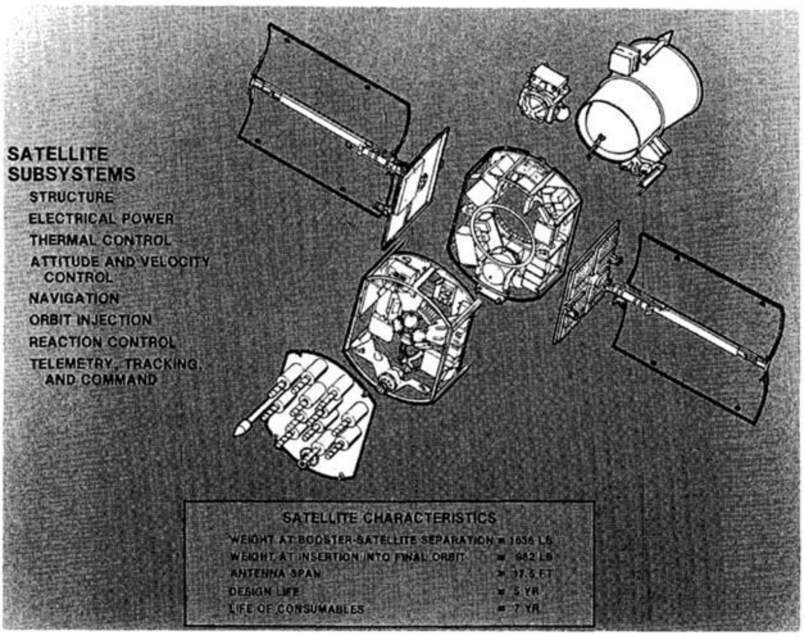

Fig. 6 Breakaway view of the GPS Phase I satellite design (drawing courtesy of the U.S. Air Force).

*The requirement for received power on L_1 is -163 dbw into an isotropic, circularly polarized antenna on the primary frequency.

standards, insuring that all satellites' clocks remained synchronized. As mentioned, NRL had been developing frequency standards for space, so this effort was continued and extended.

Payoff of a Good Clock

The basic arithmetic can be understood as follows: A day is about 100,000 s, or 10^5. Light travels about 1 ft per ns (10^{-9} s). If the system can tolerate an error buildup caused by the atomic clock of 5 ft, the stability must be 5 ns per upload (one-half a day). This is about $(5*10^9)/(5*10^4)$ sps, measured over 12 h. Therefore, this requirement is for a clock with about one part in 10^{13} stability,* which can only be met by an atomic standard. Note that there is a roughly constant frequency shift attributable to relativistic effects (both special and general) of about 4.5 parts in 10^{10}, which is compensated by a deliberate offset in the clock frequency.

GPS traditionally has used two types of atomic clocks: rubidium and cesium. Phase one test results for the rubidium cell standard are shown in Fig. 7. A key to outstanding satellite performance has been the stability of the space-qualified atomic clocks, which exceeded the specifications. They have measured stabilities of one part in 10^{13} over periods of 1–10 days.[3]

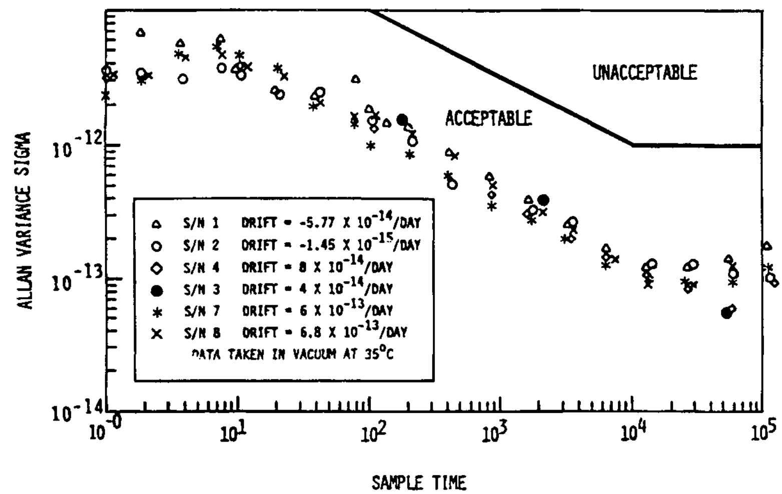

Fig. 7 Space qualified rubidium-cell frequency standard performance. These units were developed by Rockwell as a derivative of a clock designed by Efratom, Inc. (data courtesy of the U.S. Air Force).

*Clock stability is traditionally measured with the Allen variance, which shows stability versus averaging time. For short averaging times (1 s) virtually all clocks are dominated by the quartz oscillator, which acts as the short-term flywheel. In Phase one, the clocks were specified at 10^{-12}, measured over 1 day.