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Precise measurement of time, applications to astronomy and navigation

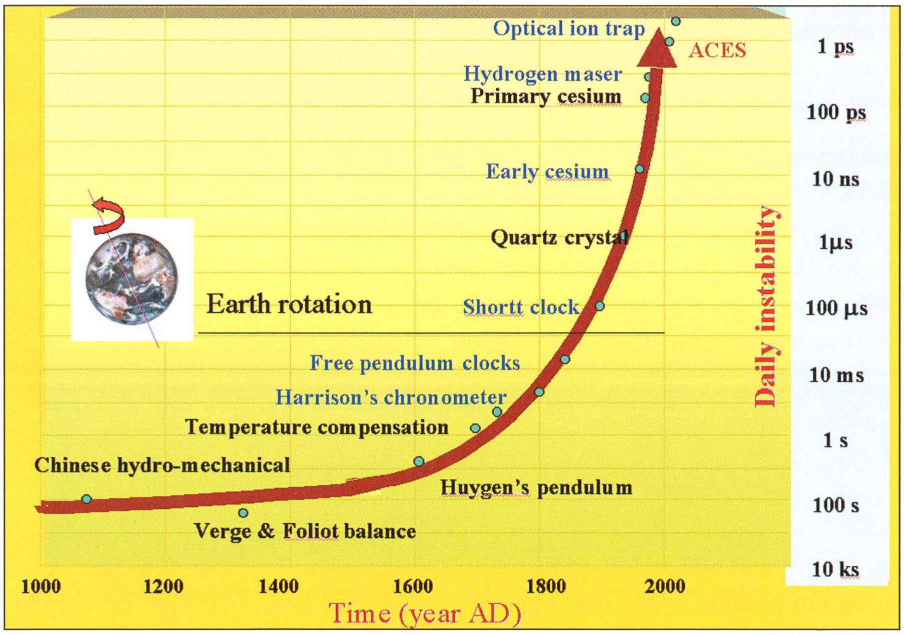
PIERRE THOMANN

Introduction

Time flies… once measured, no time interval ever happens again to be measured a second time. Nevertheless, it is time, among all physical quantities, that can be measured with the highest precision. Time is measured by clocks, but there are different types of measurements that require different types of devices. At a coarse level, one requirement of time-keeping is to keep track of events, and record them on an unambiguous scale. This is the requirement for a reliable calendar, which has always been fulfilled with the help of astronomical phenomena such as the earth rotation, lunar and seasonal cycles. The need for human-made devices arose when subdivisions of a day were needed to better control the timing of human activities.

Most present day clocks make use of some periodic phenomenon to produce a regular sequence of impulses, the familiar ticking of mechanical clocks. Examples of such periodic phenomena are oscillations of a pendulum or of a quartz crystal, and internal oscillations of individual atoms. Maintaining the regularity of these oscillations over long periods of time is the main problem of clock making. Since perpetual motion does not exist, any oscillator must be supplied with energy to maintain a constant oscillation level. On the other hand, any exchange of energy between the oscillator and its environment degrades the stability of its oscillations. One way out of this dilemma is to select a natural oscillator which requires very little energy or, in other words, which can oscillate without energy supply for a very large number of periods before its oscillation amplitude has decreased appreciably. This number is called the quality factor Q of the resonator. It typically amounts to a few hundred for a pendulum, and a few million for good quartz crystals. For atoms, it ranges from 10^7 to 10^{15}, depending on the type of atom and the type of resonance inside a given atom, and on the way the atom is confined in the resonator. It is actually often limited by the time during which an atom can be observed *and* kept protected from collisions with other atoms or with the walls of the container. In addition to having a high quality factor, atoms of a given species are identical: in contrast to pendulums and quartz crystals, whose oscillation frequencies depends on their dimensions, the frequencies provided by atoms are «natural constants». These two characteristics explain the very fast development of chronometry since the advent of atomic clocks in the 1950's.

Fig. 1: Evolution of time-keeping.



Chronometry and timekeeping

In many applications, such as telecommunications, the device capable of generating a regular sequence of impulses is all that is needed. This is called a frequency standard. The analogous of a frequency standard in the field of length measurement would be a ruler with perfectly equidistant graduations of well known separation, but without any numbers attached to them. Adding the numbers (of millimeters or centimeters along the ruler) amounts to adding a counting device to the frequency standard, to turn it into a clock. In some applications, such as tracking of planetary probes, clocks use the simple start/stop function as in a stopwatch to precisely measure time intervals without specific reference to time of day. Finally, setting the time displayed by the clock to an arbitrarily defined, but internationally accepted reference time scale, a process known as «synchronization», turns the clock into a time-keeping device. The time during which the clock can be allowed to run before a new synchronization is needed depends on the stability of its frequency standards, and the accuracy required from the clock.

One common way of characterizing the performance of man-made clocks is to use two or more of them to measure the length of a same time-interval, for example one day, repeating the same operation over many days. The differences between the clock readings at the end of each daily measurement are then analyzed statistically to provide an estimate of the «precision», or rather, the stability of these clocks. Figure 1 shows the progress of clock performance over the last centuries. The performance of clocks here is arbitrarily measured by the residual, uncontrolled day-to-day fluctuation of their reading for a one-day time interval measurement, or *daily instability* for short. The daily instability started at tens of minutes for the first mechanical clocks of the middle-ages, then improved from seconds with Galileo's and Huygen's invention of the pendulum clock to milliseconds with their ultimate refinements in the first part of the 20th century. After ca 1930, the Earth rotation ceased to provide a stable enough reference, and comparisons were made between clocks of similar performance.

Principle of operation of atomic clocks

A block diagram of an atomic clock is shown in Figure 2. Atoms are confined in a vacuum vessel in the form of a vapor or an atomic beam: mutual colli-

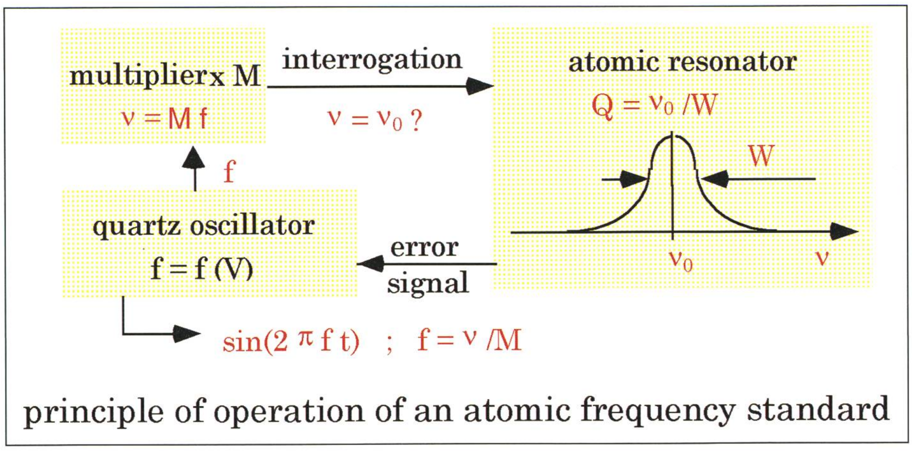


Fig. 2: Block-diagram showing the principle of operation of an atomic clock.

sions of atoms in a liquid or solid phase would ruin the stability of their oscillations. They are irradiated by an electromagnetic wave at a frequency which is a fixed multiple of the oscillation frequency f of a quartz oscillator. The frequency f may exhibit several types of unwanted instabilities, due e.g. to temperature changes or to ageing.

The atomic resonator is used as a frequency reference and discriminator to detect these changes: when n is close to the atomic resonant frequency, the energy absorbed from the electromagnetic wave by the atoms goes through a sharp maximum. Detecting the amount of energy exchange with the atoms provides a quantitative measure of the frequency difference $n - n_0$. This knowledge can then be used to steer the quartz oscillator frequency in order to maximize the atomic response, i.e. to maintain n very close to its desired reference value n_0. This steering operation «locks» the quartz frequency to the atomic frequency ($f = n_0/M$), thereby compensating for the changes due to temperature and ageing.

An atomic clock is thus basically a quartz oscillator whose frequency is actively controlled to stay very close to some predetermined fraction ($1/M$) of the atomic frequency, literally transferring to the quartz oscillator the inherent stability, reproducibility, and insensitivity to environmental conditions of the atomic resonance.

Characterization of clocks

Daily instabilities are just one aspect of clock characterization. One gains a much more detailed knowledge of any specific type of atomic clock by repeating the kind of measurement outlined above not only for one-day periods, but over a whole range of values of the measuring time t. Plotting the average, relative frequency difference $s_y(t)$ (statistical deviation s of the random variable $y = dn/n$, averaged over the measuring time t) between two similar standards as a function of the measuring time interval t yields curves of different shapes for different types of standards (Figure 3)

In the short term, the residual frequency instability of most types of standards is caused by random fluctuations of the error signal, usually related to the limited number of atoms contained in the resonator. These fluctuations average out more efficiently the longer the time interval, hence the better stability when t increases. In order to the performance of atomic standards in this range, ways must be found to increase the number of available atoms, and/or to reduce the line-width of the resonance. In the large t-regime, the stability of atomic clocks is determined mostly by their residual temperature sensitivity, and more generally, by their environmental sensitivity. Frequency drift, identifiable by a positive slope (+1) of the Allan deviation curve, is characteristic of atomic resonators where atoms are confined in a bulb. Atom-wall collisions induce a shift of the atomic resonance frequency which changes slowly with time due to ageing of the surface. This is true for rubidium and hydrogen frequency standards. On the other hand, atomic beam devices show a better stability over long measurement times, but the limited number of atoms available in an atomic beam increases their short-term instability.

Types of commercially available clocks and applications

Characteristics of the frequency stability, together with issues like size, cost, and power consumption, determine the fields of application of the various types of atomic clocks.

Rubidium cell clocks are the most compact (<200cm^3) of all atomic clocks and provide better long-term stability than the best quartz oscillators. Their main field of application is in the telecommunication and instrumentation in-

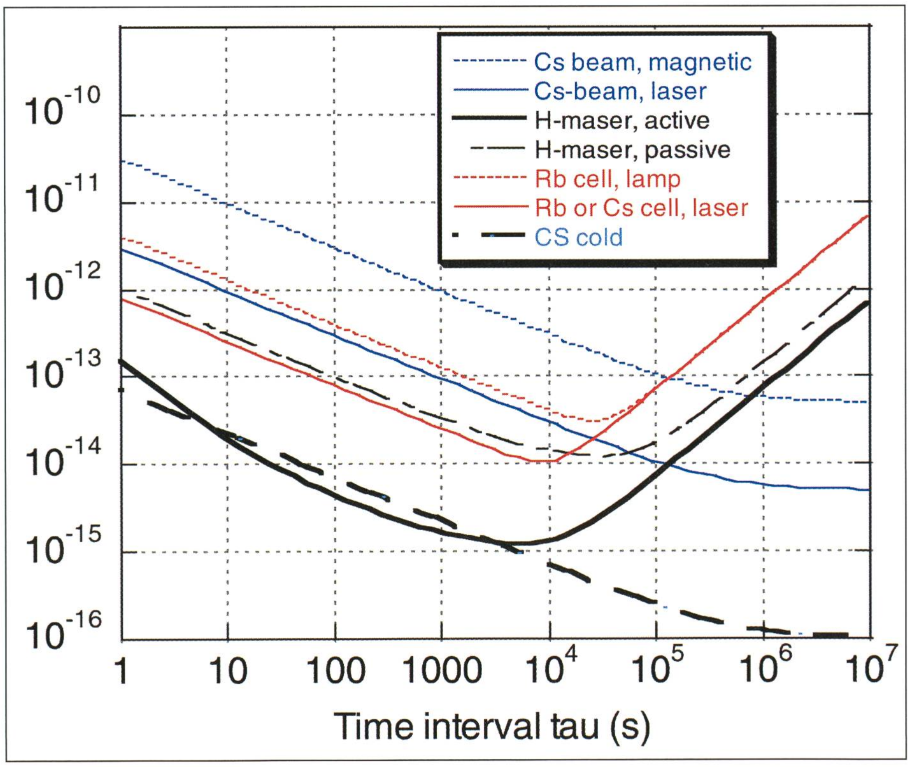


Fig. 3: Allan-deviation plot of several types of atomic frequency standards.

dustries. They are also used in navigation satellites because of their small size. Worldwide production rate is approximately 10'000/year. It will increase tremendously if efforts presently aimed at a further drastic miniaturization (1cm^3) eventually succeed.

Cesium clocks, which are atomic-beam devices, have the best long-term stability of all available atomic clocks. The unit of time in the International System of units, the SI second, is defined since 1967 as the duration of 9'192'631'770 oscillations of the cesium atom in its lowest energy state. This choice was in part guided by the exceptional long-term stability of cesium clocks, and by their ability to generate the «correct second» without calibration, a property referred to as *accuracy*. The main applications of cesium clocks is in time-keeping (generation of international time-scales TAI and UTC), network synchronization, and radio-navigation (ground- or satellite-based). Commercial cesium clocks are produced at a rate of several hundreds/year, and there are a dozen primary standards in national metrology laboratories.

Hydrogen masers are the bulkiest of all atomic standards, but they provide the best frequency stability over short and medium-term (up to one day). That is the main reason for their wide use in radio-astronomy, as described below. They are also used as complements to cesium clocks in metrological applications, and for the generation of the international time-scale. About a dozen of active hydrogen masers are produced annually in the world.

Applications in astronomy

Hydrogen masers are used by radio-astronomers in an observational technique known as Very Long Baseline Interferometry (VLBI). The basic principle, shown in Figure 4, is an elegant and powerful way of bypassing the fundamental angular resolution limit set by diffraction for a single antenna. The best angular resolution attainable with a dish of diameter D (typically 25m) detecting microwaves of wavelength l (typically 1cm) is approximately l/D radians. For all practically realizable parabolic antennas, this resolution is orders of magnitude lower than what can be obtained in the optical range.

The VLBI technique consists in creating a network of distant, individual radio-telescopes. Observing the same source with several radio-telescopes does not in itself improve the angular sensitivity. In order to achieve this, microwaves from a distant source are recorded simultaneously at all sites for as long as possible (observation time is limited by Earth's rotation). The crucial point is to superimpose an extremely stable time scale on the measurement, i.e. to provide a precise timing of the recorded waveforms. By later correlating the records from all observation sites, it is possible to determine with very high precision the delay, or difference of arrival time at the different sites. This delay information is valuable because it is related to two most interesting parameters: the distances between each pair of antennas, which are also called the lengths of the baselines, and the relative orientation between each baseline and the line-of-sight to the astronomical source. These two pieces of information are each interesting in their own right, but the raw measurement only gives a combination of them, which in addition depends on the earth's orientation and rotation rate. The measurements are however made in such a way that the relevant data can be disentangled. The measurement procedure alternates observations of reference, «point-like» sources (very distant quasars) with observations of other, extended sources whose shape and map is to be determined. Based on highly redundant measurements, powerful algorithms allow radio-astronomers to obtain from each session a bounty of meaningful results:

- baseline length: the baselines, typically thousands of kilometers long, can be determined to the centimeter level, which provides useful information on continental drift if the telescopes are on different tectonic plates;
- «real-time» baseline orientation in a reference frame given by the set of distant, point-like quasars, which provides information on the instantaneous Earth rotation rate and its various fluctuations, and on the instantaneous orientation of the Earth rotation axis (polar motion);
- maps of the luminosity (in the microwave range) of astronomical objects and structures and their time evolution. The angular resolution attainable in principle by the VLBI technique is that of a virtual dish the size of the network. For dishes scattered around the globe, this amounts theoretically to a five-order-of-magnitude improvement over single dish observation, but the actual resolution, still about 1000 times sharper than the Hubble telescope in visible light, is in practice limited by the combined effect of atmospheric fluctuations, signal detection bandwidth… and clock offset and drift, which the VLBI observations even help to measure as a by-product of astronomical and geophysical data!

Future VLBI observations with networks of space-based antennas will considerably extend the baseline lengths and the achievable resolution. The VLBI technique is also being applied to optical telescopes, where the role of the clock is played by highly stabilized lasers.

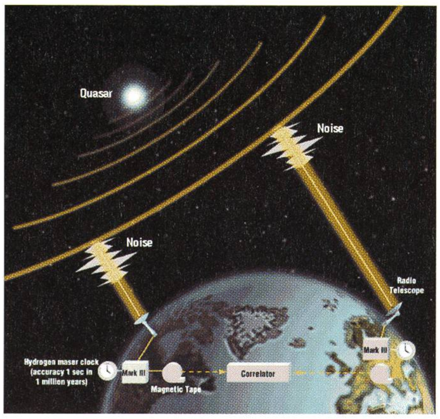


Fig. 4: Principle of VLBI.

Applications in metrology and physics

As already mentioned, one limitation to the quality factor of atomic resonators is the time available to probe the atomic resonator. In atomic beam standards, this time is limited by the transit time of the atoms across the vacuum vessel, which is in the ms range due to high atomic velocity imposed by the operating temperature. In the past 15 years, efficient techniques to slow down cesium and rubidium atoms with the aid of carefully engineered laser beams have given rise to a new generation of cesium clocks, where atoms are launched upwards with a low, controlled initial velocity to accomplish a short parabolic flight (like that of a tennis ball about to be served): in such atomic fountains, the Q factor is 50 times higher than in the previous generation of laboratory cesium clocks; it is now limited by Earth's gravity.

An ESA sponsored space experiment, ACES (for Atomic Clock Ensemble in Space), is designed to demonstrate that a cesium clock using laser-slowed atoms in a micro-gravity environment will approach a relative accuracy and long-term stability of 10^{-16}, a ten-fold improvement over the best ground based cold atom clocks. The experiment is planned for launch in 2006 on the International Space station. A hydrogen maser (developed by Observatoire de Neuchâtel, ON) will serve as reference oscillator for the metrological evaluation of the cold atom clock PHARAO (which is developed by Observatoire de Paris and CNES). Both clocks will then operate as a tandem to make use of each clock's best characteristics (see the two lower curves of Figure 3). This combined clock will be compared with ground clocks for metrological purposes, and will perform several tests of special and general relativity:

- improved test of the gravitational red-shift, or slowing of time near the Earth,
- test of the isotropy of the velocity of light,
- measurement of a possible drift of the fine structure constant a, which measures the strength of electromagnetic interactions. General relativity postulates that a is a constant. Some experimental evidence indicates that a could have drifted over the lifetime of the universe. This, and additional «real-time» estimates expected from the ACES experiment, could help in current attempts to unify all forces of nature in a common theoretical framework. The goal is to be able to detect a relative drift of about 10^{-16}/year between frequency standards operating with different atomic species.

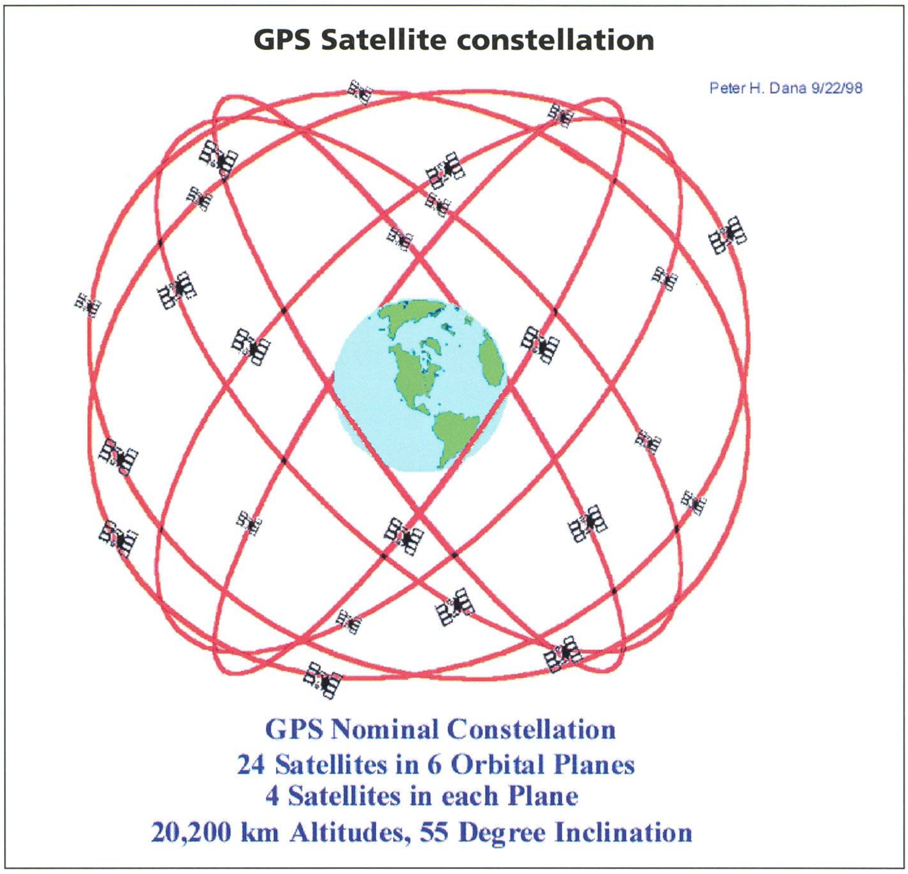
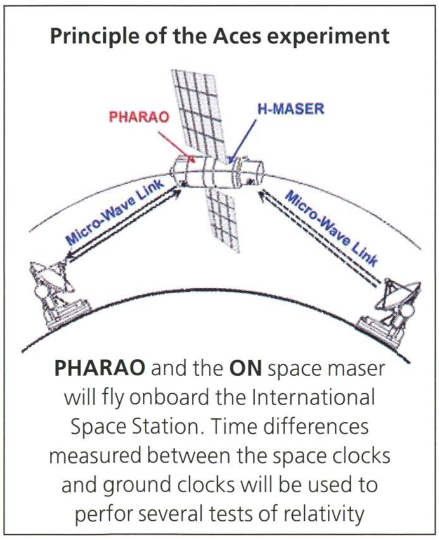


Fig. 6: Constellation of the 24 GPS satellites.

Applications to navigation

Clocks with long term stability have since long been an essential tool for global navigation. In the 18th century, HARRISON's chronometer demonstrated about 1s daily uncertainty, which was a remarkable achievement at the time it was realized. The chronometer could provide navigators with the solar time scale at the port of departure. Comparison with the solar time at an unknown location yielded the longitude of that location (15° for each hour of time difference).

Fig. 5: ACES on the ISS.



PHARAO and the **ON** space maser will fly onboard the International Space Station. Time differences measured between the space clocks and ground clocks will be used to perfor several tests of relativity

A significant step in the progress of navigation techniques was the introduction of radio-navigation techniques, of which the American LORAN-C system still is in wide use. Long-wave signals are emitted from base stations, most of them located along ocean coasts. These signals carry information about the emission time (as given by the station clock), and the station coordinates. A dedicated receiver aboard a vessel at sea measures the difference between arrival times from different stations. This delay is equal to the difference between the ship-station distances, divided by the velocity of signal propagation (30cm/ns). Three stations provide enough information to recover, by simple triangulation methods, the exact position of the ship with 100-meter accuracy. Significant advantages of such a system are that it does not require any astronomical observation (weather dependent), and that the good – and therefore expensive – clocks are located at the stations, while on-board receivers use much less expensive. Still, global coverage remains a difficult goal, and localization is limited to the Earth's surface.

In the early 1990's, the US military deployed a constellation of 24 satellites as base stations of a new, space-based, radio-navigation system (Global Positioning System). The 12-hour orbit disposition and altitude (Figure 6) guarantees that a receiver at an unknown location will at any time be able to combine data from at least four satellites. This is the minimum number required to determine unambiguously the 3-D position (longitude, latitude, altitude), together with exact time, which is a by-product of the position determination.

The GPS system consists of:

- a space segment: the satellite constellation, each satellite is equipped with four atomic clocks for redundancy. Each satellite emits coded time-signals and data providing the exact time and satellite position.
- a ground segment: 5 ground-based control stations located around the equator, in charge of determining exact satellite orbits and satellite clock drift, and updating these so-called «ephemeris» data to the satellites
- a user segment (vehicles, locations equipped with GPS receivers, whose position is to be determined)

The accuracy of localization has improved to about 25m since the intentional degradation of signal quality for civil users was abandoned in April 2000. Residual errors are due to mostly to signal propagation perturbations in the Earth's ionosphere. These can be drastically reduced, to the cm level, by measuring the ionosphere error with a reference receiver whose position is very accurately known. The same ionosphere error will indeed affect measurements with all nearby receivers and can be communicated to them by the reference receiver station to allow them to take this error into account.

Following GPS, a Russian system – GLONASS – was deployed according to a very similar concept. An European navigation system – GALILEO – is presently under development, with deployment planned for 2008. GALILEO is designed to be compatible with GPS but will be a civilian system. Users will have access to real-time information about the system health in order to guarantee safety in such applications as landing of commercial airplanes. The number and variety of applications is expected to grow very fast with the increased accuracy (<1m) for which GALILEO is designed. Requirements for the satellite clocks are stringent (1ns daily error) but are now met by the 17kg prototype hydrogen maser developed by ON (Figure 7). Two back-up rubidium clocks, produced by Temex Neuchâtel Time following a development at ON, will complement the two hydrogen clocks on each satellite.

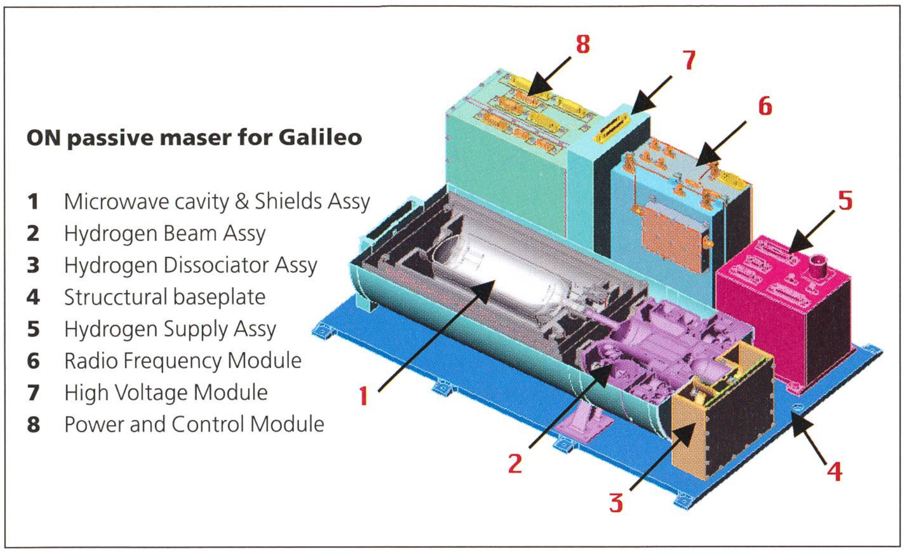


Fig. 7: ON Space passive hydrogen maser for GALILEO.

Conclusion

Since the first atomic clocks were introduced in 1955, the performance of precision chronometry has steadily increased by about a factor of 10 every decade. The development of cold atom clocks with 10^{-15} accuracy will soon be followed by atom or ion clocks at optical frequencies, which are most likely to continue the present trend.

Although the precision of time measurements is better than that of any other physical quantity, applications such as satellite navigation systems continue to be a driving force towards further developments. Scientific applications in space-based experiments may be one field where even better clocks than presently available will be needed.

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