Predicting the Future of Atomic Clocks Using the Theory of Evolution

by

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Abstract

The trend of technology evolution plays a very important role to understand how and why products evolve over time and define strategies of further improvements of products. The trend of evolution is based on the fact that all the products, process or technical systems will evolve over time.

A cesium atomic clock is the most accurate realization of a reference unit that mankind has yet achieved. The commercial cesium atomic clock is very mature and the demand for this type of clocks expected to be flat. A size reduction is possible due to new physics improvement by using optical pumping technique, but no major changes in performance and prices are expected.

The masers outperform the high performance cesium clocks for a time period of sub seconds to one day. The hydrogen maser is very mature product like cesium and the design has remained the same for the last 30 years. The product is expected to remain as presently available.

Rubidium atomic clocks provide enhanced accuracy, stability and timing precision compared to quartz-based technologies. This market is large enough to support continuing technological innovation. The world's first commercially available miniature developed by Symmetricom in 2008 marks a major step toward in the evolution of rubidium atomic clocks. It is predicted that future of rubidium oscillators will be based on coherent population trapping technology. The miniature rubidium clocks will be smaller, cheaper, and will be operated by small batteries.

Acknowledgments

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Chapter I. Introduction

1.1 The Clock in Nature

Ancient civilizations relied upon the Sun and the Moon, the two most important visible astronomical objects in the sky, to determine seasons, months, and years. The cycles of the planets are very important in the creation and understanding of calendars. Over 20,000 years ago, ice-age hunters in Europe scratched lines and groove holes in sticks and bones, counting the days between phases of the moon [1]. 5000 years ago, Sumerians had a calendar that divided the year into 30 day months, divided the day into 12 periods which each corresponding to 2 of our hours, and divided these periods into 30 parts which each equaled 4 of our minutes [1]. The Egyptians had been developing their own system since 3100 BC, based on the moon's cycles, but ran into problems very quickly. Egypt is unique in early civilization in being dependent on flooding of Nile River. Egyptians realized that the "Dog Star" in which we call Sirius, rose next to the sun every 365 days, about when the annual inundation of the Nile began. Based on this knowledge, they devised a 365 days calendar, which thus seems to be one of the earliest years recorded in history [1, 2]. The Babylonians used a year of 12 alternating 29 day and 30 day lunar months, giving a 354 days year in 2000 BC. Before 2000 BCE, the Babylonians (in today's Iraq) used a year of 12 alternating 29 day and 30 day lunar months, giving a 354 days year [1].

In contrast, the Mayans of Central America relied not only on the Sun and Moon, but also tracked the morning star rise of Venus, which occur every 584 days. Two cycles involved in this calendar system were the vague year of 365 days (the kaab) and sacred cycle of 260 days (the tzolkin) [1]. The kaab and tzolkin synchronize with each other every 52 years. This culture and its related predecessors spread across Central America between 2600 BC and 1500 CE, reaching their apex between 250 and 900 CE [1]. They left celestial-cycle records indicating that the creation of the world occurred in 3114 BC according to their belief. Their calendars later became portions of the great Aztec calendar stones [1, 3]. Figure 1.1 show the picture of Aztec calendar, which is on display at the National Museum of Anthropology in Mexico City. Our present civilization has adopted a 365-day solar calendar with a leap year occurring every fourth year.

Figure 1.1 The sun stone also called the Aztec calendar on display at the National Museum of Anthropology in Mexico City.

1.2 Sun Clocks

For thousands of years Earth, moon and the Sun were sufficient to regulate daily activities. The people got up and began their wok at sunrise, rested and ate the meal about noon and finished work at sunset. They didn't have the need to know time any more accurately than this. 5,000 to 6,000 years ago Great civilizations in the Middle East and North Africa initiated clock making more efficiently [1]. Egyptian built the Obelisks as early as 3500BC whose moving shadows provided an easy way to chart the course of the day [1, 4]. An obelisk is a tall, narrow, four-sided, tapering monument, which ends in a pyramidal top (see Figure 1.2). Later, additional marks around the base provided the better accounting of the day [1, 4].

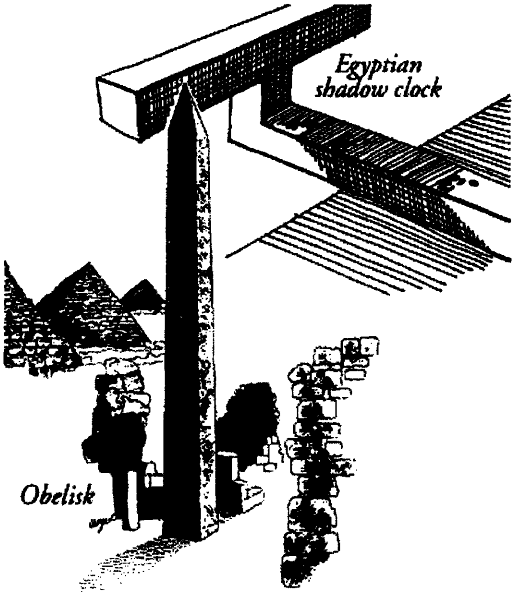

Figure 1.2 Egyptian Shadow Clock [1].

By 1500 B.C., the Egyptians had developed portable shadow clocks or sundials. The sundial is divided a sunlit day into 10 segments plus two more divisions "twilight hours" in the morning and evening [1, 4]. In the morning the long stem with 5 variably spaced marks was oriented east and west, and the elevated crossbar on the east end cast a moving shadow over the marks. At noon, the timing device was turned in the opposite direction to measure the hours in the afternoon [1, 4]. Figure 1.3 showing an ancient sundial.

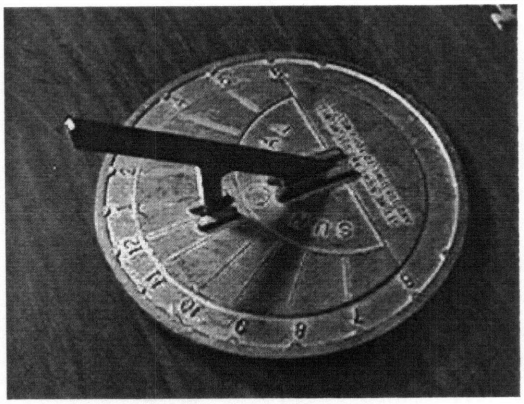

Figure 1.3 An Ancient Sundial [5].

The Egyptians also used their knowledge of time to develop astronomy tools. The Egyptians used a star clock or merkhet to measure the time at night around 600 BC [1]. A pair of merkhets was used to line up with the pole star and mark out a north-south line (see Figure 1.4). The device was used at night to mark off hours by determining when certain other stars crossed the meridian. The merkhet belonged to an Egyptian priest called Bes, son of Khonsirdis, who was the Observer of Hours at the Temple of Horus in Edfu, Upper Egypt [1] .

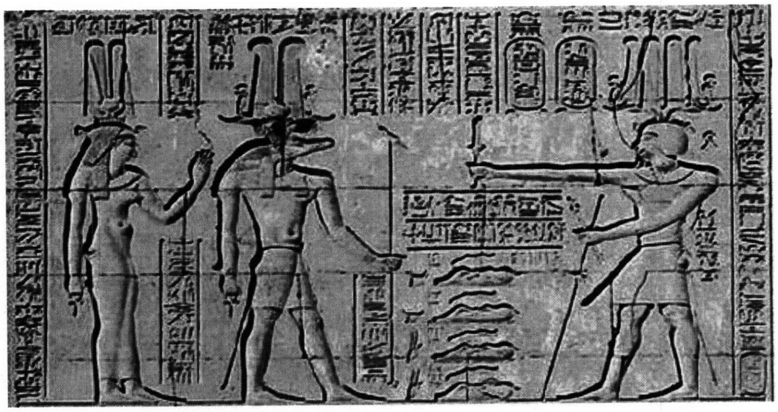

Figure 1.4 Showing the Use of the Merkhet to Determine a True North-South Line [6].

1.3 Water Clocks

The earliest water clocks were built in Egypt around 1400 BC. Water clocks were among the first timekeepers that didn't depend on the observation of other planets [1, 4]. The water clock was used to tell time and to measure speeches in the courtroom [1, 4]. The water clock in its simplest form consists of a bowl that had a small hole located near the base. Hours were marked on inside with horizontal marks. These early clocks were used when equal measurements of time needed to be established. A simplified concept of water clock is shown in Figure 1.5.

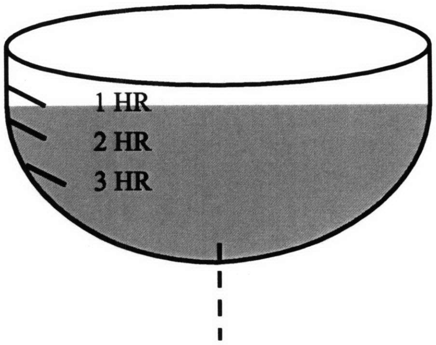

Figure 1.5 Simplified Concept of Water Clock.

More impressive mechanized water clocks were developed between 100 BC and 500CE by Greeks and Romans [1, 4]. Sometimes between the 8th and 11th centuries AD the Chinese built a clock that had some of the characteristics of later mechanical clocks [see Figure 1.6]. Many variations of the Chinese water clocks were constructed, and they become very popular by the early 13th century [1, 4]. Since the rate of water flow is very difficult to control, clocks never achieve excellent accuracy and people were led to develop other approaches.

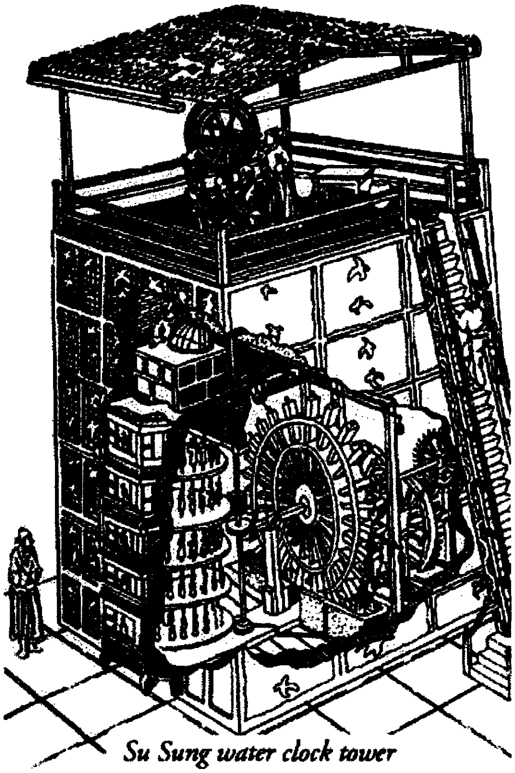

Figure 1.6 14th Century Chinese Water Clock [6].

Today, in Beijing's Drum Tower, an outflow clepsydra is operational and displayed for tourists [see Figure 1.7].

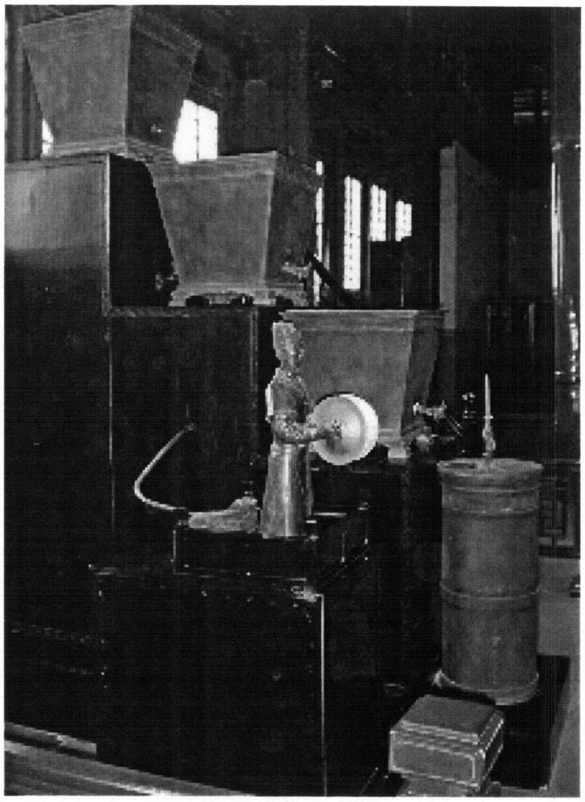

Figure 1.7 Beijing's Drum Tower.

1.4 Sand Clocks

Sand clocks were introduced in the 14th century to avoid the freezing problem. Sand clocks were limited to measure short time interval due to the weight of the sand. The sand clocks ware used by sailors as a timekeeper and to find the speed of the ship [4]. For measuring speed a log line was thrown overboard, in which knots had been tied at regular intervals. By counting how fast the knots appeared, they could reckon how many "knots," or nautical miles an hour the ship traveled [4]. The picture of a sand clock in Figure 1.8, made by Tom Young, is a replica of a 16th century glass found off the coast of Canada [7].

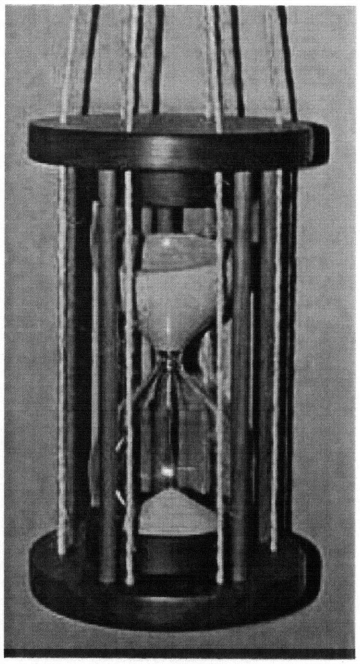

Figure 1.8 Replica of a 16th Century Sand Glass.

1.5 Mechanical Clocks

1.5.1 Verge and Eliot Foliot Clocks

The first mechanical clock came to use came into use sometime around 1285 [4]. These mechanical clocks had a verge and foliot, which were used for the mechanism that sounded a bell [see Figure 1.9]. The name clock, which originally meant bell, came into use when there were very large mechanical time indicators installed in bell towers in the late middle Ages [4, 8]. Variations of the verge and foliot mechanism reigned for more than 300 years. The period of oscillation of the escapement depended heavily on the amount of driving force and the amount of friction in the drive. Like water flow, the rate was difficult to regulate. This invention is important in the history of technology, because it made possible the development of all-mechanical clocks. This caused a shift from measuring time by continuous processes, such as the flow of liquid in water clocks, to repetitive, oscillatory processes, such as the swing of pendulums, which had the potential to be more accurate [4, 8].

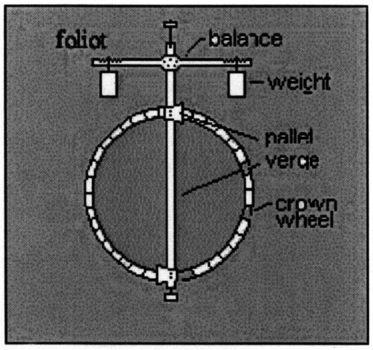

Figure 1.9 Verge and Foliot Clock [5].

1.5.2 The Pendulum Clocks

The period of the mechanical clock depended on a number of complicated factors such as friction between the parts, the driving force and the skill of the craftsman. These clocks were not keeping accurate time and no two clocks were showing the same time [4]. What was needed was a periodic device for which frequency was a property of the device itself and did not depend primarily on a number of external factors. A pendulum is such a device. Galileo Galilei [1564-1642] is credited with first realizing that the pendulum could be the frequency-determining device for a clock as early as 1582 [4]. He noted that the period of pendulum depended upon its length and not on the magnitude of the swing or the weight of the mass at the end of the string. The story goes that he came to this conclusion by watching the swings of the bronze chandelier in the cathedral of Pisa, using his pulse to time it [4]. Later work showed the period does depends slightly upon the magnitude of swing. This correction is very small as long as the magnitude of the swing is small. He even sketched out a design for a pendulum clock, but never constructed one before his death in 1642 [4].

In 1656, Christiaan Huygens [1629-1695], a Dutch scientist, made the first pendulum clock, regulated by a mechanism with a natural period of oscillation which greatly increased the accuracy of time measurement [1, 4, 9]. His early clock had an error of less than 1 minute a day, far more accurate than any previous timepiece. His later refinements reduced his clock's error to less than 10 seconds a day [4].

Around 1675, Huygens developed the balance wheel and spring assembly [4]. At the same time Robert Hooke [1635-1703], an English scientist, was experimenting with the idea of using a straight metal spring to regulate the frequency of a clock [4]. Huygens used a spiral spring, whose derivative the "hair spring" is still employed in watches today [4].

1.5.3 Need for More Accurate Mechanical Clock for Navigation

One of the earliest, universal needs for precise time information was and still is as a basis for location and navigation. Navigating ships at sea and planes in the air depends constantly and continuously on time reference information to find out where they are and to chart their course. In the 15th century, explorers took to the seas in the search of new worlds and treasures. It was already known that Sun and stars could aid them in their journeys where there are no familiar signposts [9]. Early explorers in the northern hemisphere were fortunate in having a pole star (North Star) that appeared to be suspended in the northern sky. The North Star did not rotate or change its position with respect to Earth as the other stars did. They also noticed that as they traveled northward, the North Star gradually appeared higher and higher in the sky. By measuring the elevation of the North Star above the horizon, they could determine their distance from the North Pole and, conversely, their distance from the equator. To navigate, sailors were able to determine their latitude by using a sextant to observe the position of the sun at the midday or bright stars at night. A sextant is a measuring instrument used to measure the angle of elevation of a celestial object above the horizon [10] (see Figure 1.10). The angle, and the time when it was measured, can be used to calculate a position line on a nautical or aeronautical chart [10]. A common use of the sextant is to sight the sun at noon to find one's latitude. The measurement is usually indicated in degrees of latitude, ranging from 0 degrees latitude at the equator to 90 degrees of latitude at the North Pole [10].

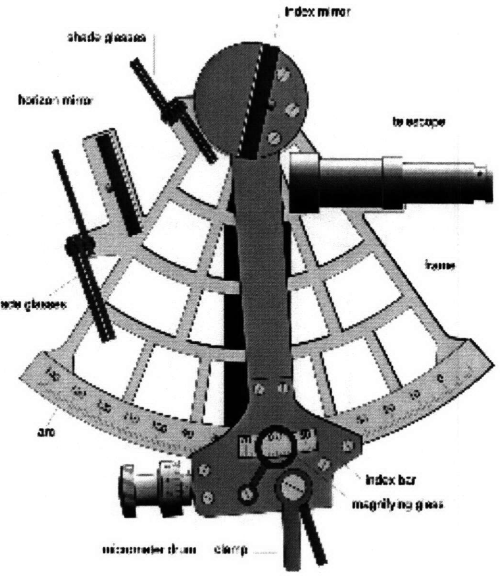

Figure 1.10 Marine Sextant.

Measuring longitude was more difficult to measure due to earth rotation [10]. If only they had a clock aboard that could tell them the time at Greenwich, England; they could of easily find their position west or east of zero meridians [10]. Measuring longitude requires both a sextant and an accurate clock. In the 15th century and 16th centuries, clocks were insufficiently accurate to navigate with any certainty, and this all too often led to disaster.

In 1707 Admiral Sir Cloudesly Shovell miscalculated his position and struck and wrecked his flagship HMS Association on the rocks near the Isles of Scilly [9] with three other British warships. His miscalculation led to the loss of nearly 2,000 lives, including his own. Even though his main error was estimating the latitude, complicated by fog so thick that he could see neither night sky nor daytime sun, longitude continued to be the biggest source of error [9].

The British Government took an action in 1714 to solve the problem of finding longitude at sea [9]. The board of longitude gathered the greatest scientific minds of its day to work on the problem. Sir Isaac Newton appeared before the House of Commons in 1714 and spoke on the determination of longitude at sea [9]. The board offered the longitude prize of 20,000 pounds (equivalent to millions in today's currency) for those who could demonstrate a means of resolving position at the sea to within 30 nautical miles or longitude within half a degree [9]. This required a clock to keep track of time within 3 seconds per day.

In 1730, John Harrison, a woodworker, and musicians from Lincolnshire created drawings for a proposed clock to compete for the prize and went to London for financial assistance [4, 8]. George Graham, the country's foremost clockmaker, personally loaned Harrison money to build a model of his marine clock [4, 8]. It took Harrison seven years to build Harrison Number One or H1 [see Figure 1.11]. The H1 resolved the position at the seat trial to within 60 nautical miles and the board granted Harrison 500 pounds for further development.

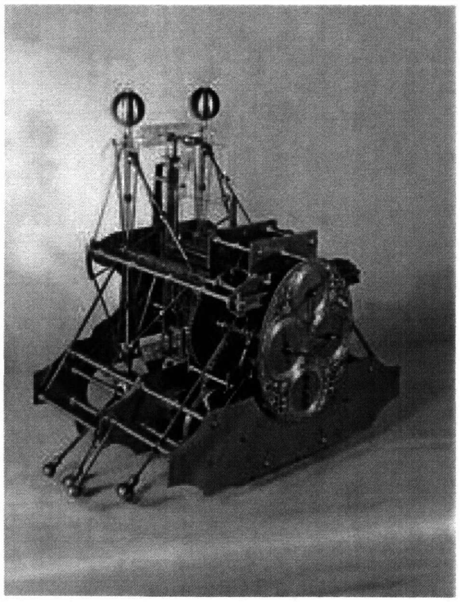

Figure 1.11 Marine Timekeeper (H1)

National Maritime Museum, London (1735)

Harrison completed the design of H4 [see Figure 1.12] at the age of 68 and sent it for transatlantic trial in 1761 [4, 8]. This clock kept time accurate to one second per day. When the ship returned Harrison waited for the 20,000 pounds prize, but the Board believed the accuracy was just luck, and demanded another trial. Harrison demanded his prize and the case went to British Parliament, which offered 5,000 pounds for the design. Finally, Harrison appealed directly to King George III, who, compassionate to Harrison's plea, and applied pressure on Parliament to award the balance of the prize money. Using a copy of Harrison's clock, Capitan James Cook mapped the Polynesian islands and the Pacific Ocean regions [11]. In his log book for the new navigational instrument he wrote "our trusty friend the watch" and 'our never failing guide [11]." The accuracy of Harrison's clock was about one-fifth of a second a day.

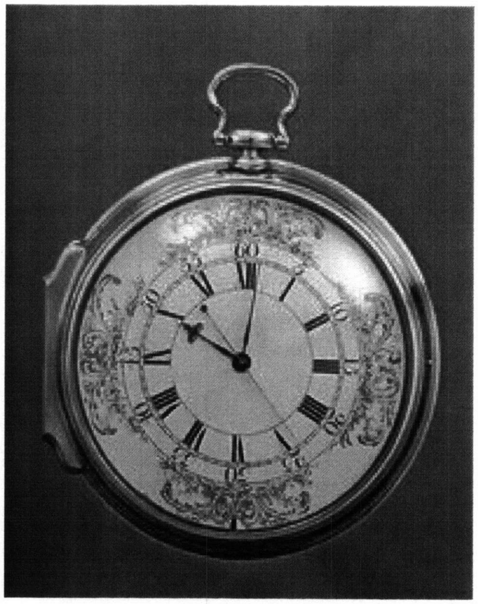

Figure 1.12 Marine Timekeeper (H4)

National Maritime Museum, London (1759)

Having clocks with good long-term accuracy, navigators now needed to synchronize their chronometers to a central clock. In Britain, ships would sail up the Thames and watched a ball drop from a tower at the Greenwich observatory at precisely 1:00 P.M [12]. Other nations such as Portugal and France with large navies had their own standard time and debate raged over which meridian should be used for standard time [12].

1.5.4 Double Pendulum Clocks

The introduction of the pendulum was one of the biggest steps in the history of time keeping. Attempts to defeat of some difficulties such as friction and expansion and contraction of pendulum to improve accuracy led to a clock that had two pendulums. In 1921 William Hamilton Shortt [1881-1971], a British railway engineer and director of the Synchronome Co Ltd, succeeded in devising a system to keep two pendulums in precise sympathy [4]. The free pendulum was the frequency-keeping device, and the slave pendulum controlled the release of energy to the free pendulum and counted its swings. This type of clock kept time within a few seconds in five years [4].

1.6 The Quartz Clocks

The new approach was needed to improve the accuracy of the clocks since Hamilton Shortt, perfected the accuracy of the mechanical clocks.

In the early 20th century, as radio broadcasting stations matured and telephone wires carried more messages, maintaining stable electrical frequencies and planning to monitor the frequencies became critical technical problems [13]. In 1927, Canadian-born Warren Marrison [1896-1980], an electrical engineer, was searching for reliable frequency standards at Bell Telephone Laboratories [13]. Building on earlier work in piezoelectricity by W.G. Cady and G.W. Pierce, he developed a very large, highly accurate clock based on the regular vibrations of a quartz crystal in an electrical circuit [14]. During the 1940s, time standard laboratories throughout the world switched from mechanical clocks to quartz [14]. The fundamental standard of time remained the rotation of the earth relative to the stars, but quartz clocks confirmed that the earth was an unreliable timekeeper [13, 14]. In 1969, Seiko produced the world's first quartz wristwatch, the Astron [15]. The Astron was accurate to ±5 seconds per month, or one minute per year [14]. The typical wristwatch has as its frequency standard a quartz crystal tuning fork with an oscillation frequency of 32,768 Hz [9]. This number of oscillations is continent in digital electronics circuit, because if it is divided by 2^{15}, which is easy for a digital chip divider, the result is one cycle or pulse per second [9]. The best crystal clocks will keep time within less than 1 millisecond per month and lower quality quartz clock may drift a millisecond or so in a few days [4]. One of the most important traits of quartz crystal oscillators is that they can exhibit very low phase noise [14]. In many oscillators, any spectral energy at the resonant frequency will be amplified by the oscillator, resulting in a collection of tones at different phases. In a crystal oscillator, the crystal mostly vibrates in one axis. Therefore, only one phase is dominant. This property of low phase noise makes them particularly useful in telecommunications where stable signals are needed and in scientific equipment where very precise time references are needed. Environmental changes of temperature, humidity, pressure, and vibration can change the resonant frequency of a quartz crystal, but there are several designs that reduce these environmental effects. These include the Temperature Controlled Crystal Oscillator (TCXO), Microcomputer Compensated Crystal Oscillator (MCXO), and Oven Controlled Crystal Oscillator (OCXO) [14]. These designs and mostly the OCXO often produce devices with excellent short-term stability [14]. The limitations in short-term stability are due mainly to noise from electronic components in the oscillator circuits. Long term stability is limited by aging of the crystal. Due to aging and environmental factors such as temperature and vibration, it is hard to keep even the best quartz oscillators within one part in 10−E10 of their nominal frequency without constant adjustment. For this reason, atomic oscillators are used for applications that require better long-term stability and accuracy [4]. Although crystals can be fabricated for any desired resonant frequency, within technological limits, in actual practice today engineers design crystal oscillator circuits around relatively few standard frequencies, such as 3.58 MHz, 10 MHz, 14.318 MHz, 20 MHz, 33.33 MHz, and 40 MHz [14]. Using frequency dividers, frequency multipliers and phase locked loop circuits; it is practical to derive a wide range of frequencies from one reference frequency [14].

1.7 The Atomic Clocks

The development of radar and extremely high frequency radio communications in the 1930s and 1940s made possible the generation of the kind of electromagnetic/microwave needed to interact with atoms[4]. Research aimed at developing an atomic clock focused first on microwave resonance in the ammonia molecule. The idea of an atomic clock was proposed in the early 1940s by Nobel laureate I.I. Rabi [4]. The first atomic clock, based on a microwave resonance in the ammonia molecule and using the microwave resonance of ammonia molecule, was introduced to the world in 1949 by Harold Lyons of National bureau of Standards [1, 4]. Figure 1.13 is of the first atomic clock, constructed in 1949 by the US National Bureau of Standards. It operated with an ammonia-regulated quartz crystal and ran with a constancy of one part in 20 million.

Figure 1.13 First Atomic Clock, Constructed in 1949.
[NBS Director] Dr. [Edward] Condon and Dr. Harold Lyons

This was an important philosophical and scientific step towards high accuracy reference time keeping devices. Lyons's group researched the possibility of using a cesium beam as an atomic frequency standard. It was not until June of 1955 that L. Essen and J.V.L Parry of the National physical laboratory in England introduced the first operating cesium atomic clock [4]. In October of 1967, at the 13th convocation of the General Conference of Weights and Measures, it was declared that; 'The second is the duration of 9,192,631,700 periods of the radiation corresponding to the two hyperfine levels of the ground state of the cesium 133 atom." Much of modern life has come to depend on precise time [9]. The day is long past when we could get by with a clock accurate to the nearest quarter-hour. Transportation, communication, financial transactions, manufacturing, electric power and many other technologies have become dependent on accurate clocks. Scientific research and the demands of modern technology continue to drive our search for ever more accurate clocks [16].

Three types of atomic standards are available to meet frequency stability requirements which exceed the performance capabilities of quartz crystal oscillators: cesium, rubidium and hydrogen frequency standards. The principle behind all the three remains the same.

1.7.1 The Rubidium Atomic Clocks

Rubidium atomic resonance is at 6,834,682,608 Hz. Commercial rubidium standards, based on the hyperfine transition in the ground state of ^{87}Rb, are optically pumped using the light emitted from a ^{87}Rb discharge lamp [17, 18]. Light from a rubidium vapor discharge lamp (similar to a neon lamp) enters a glass cell which contains ^{87}Rb gas plus a buffer gas. The light passes through the cell and illuminates a photocell where the light is converted to an electrical signal. The quartz oscillator (similar to that in a quartz wrist watch) puts out electrical pulses each second depending on frequency of the quartz. The field is derived ultimately from the quartz controlled oscillator (typically 10 MHz). The desired microwave frequency is produced by a frequency synthesizer which, starting with the 10 MHz oscillation as reference, generates signals at multiples and submultiples of that frequency. When the multiplied frequency equals the rubidium atom frequency of 6,834,687,500 pulses per second, the rubidium light from the lamp is strongly absorbed by the rubidium atoms in the cell so that not all of the light reaches the photocell detector. This gives a weak electrical signal out of the photocell. When the multiplied frequency differs from the rubidium atom frequency, the rubidium light from the lamp is weakly absorbed by the rubidium atoms in the cell so that more of the light reaches the photocell. This gives a strong electrical signal out of the photocell [17, 18].

The feedback electronics process the error signal and produce a dc correction voltage to adjust the frequency of the quartz oscillator so that it returns to the proper vale of exactly 10 million pulses per second. Rubidium oscillators, in comparisons with quartz crystal oscillators, offer better stability in the range from one hundred seconds to a few hours, a factor of ten improvement in long term aging, superior reproducibility, and lower sensitivity to the environment. The schematic drawing of a passive rubidium frequency standard is shown in Figure 1.14.

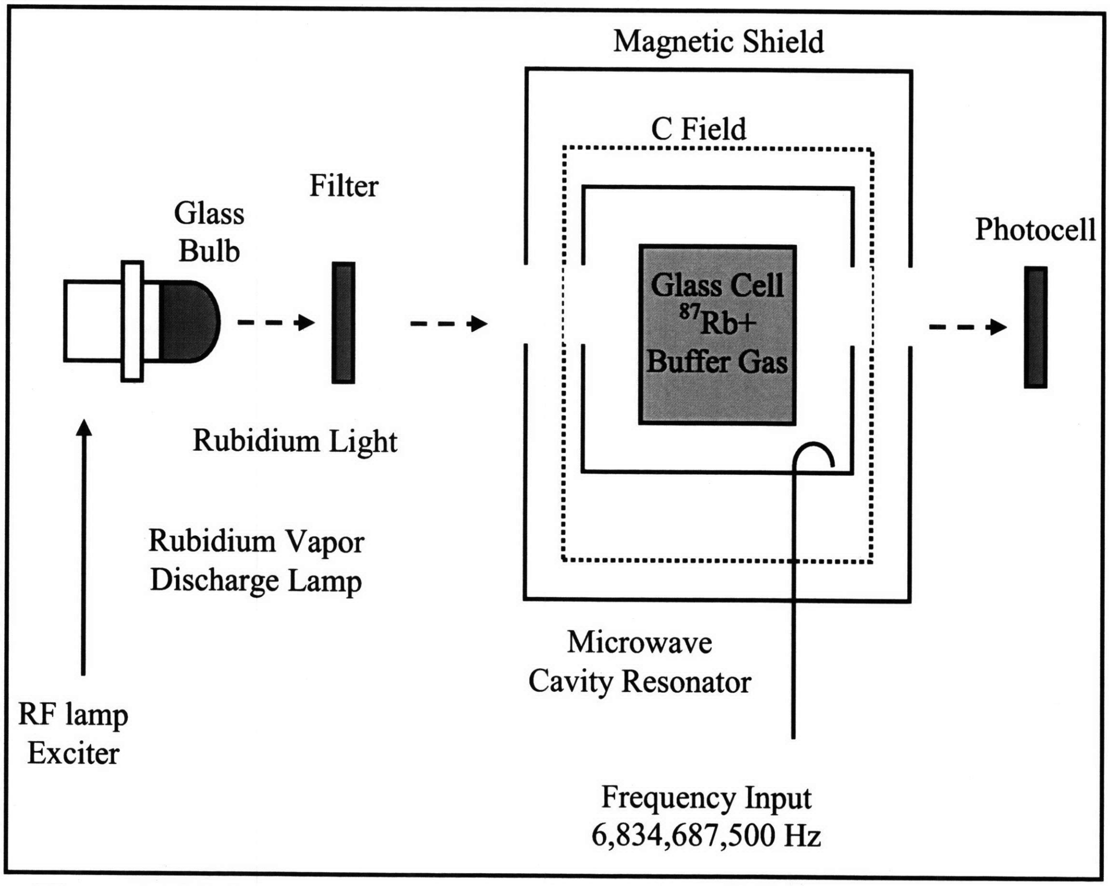

Figure 1.14 Schematic Drawing of a Passive Rubidium Frequency Standard

1.7.2 The Cesium Atomic Clocks

Cesium atomic resonance is at 9,192,631,770 Hz. Figure 1.15 is a schematic of a cesium beam tube [17]. Spectroscopy is performed on cesium atoms in free flight through the microwave cavity in order to minimize environmental influences [17]. A magnetic state prior to the cavity rejects atoms in the unwanted hyperfine level. A magnetic state selector following the cavity passes atoms having the state that was rejected in the first region. Thus, atoms must make a hyperfine transition in order to reach the hot wire ionizer. A feature of this tube is the U shaped microwave cavity called the Ramsey tube. In this design, atoms are exposed to a second microwave field, pass through a microwave field free region, and are then exposed to second microwave field, in phase with the first. As a result, the atomic line is an interference pattern that maximizes the resolution of the spectrometer. Even more important, the design of the Ramsey cavity reduces the sensitivity to magnetic field non-homogeneities. Without it, the magnetic shielding requirement would be impractical. Cs standards are more accurate than rubidium standards because the Cs atoms pass through a high-vacuum region without collisions with buffer gas molecules or walls, which cause frequency instabilities in rubidium standards. Instead of confining the atoms to a small cell, as is done in rubidium standards, usually the Cs atoms travel through the ends of a relatively long microwave cavity giving the double-pulse Ramsey excitation [17]. Figure 1.15 shows a typical electronic schematic for the cesium frequency standard. The electronic schematic of frequency locks to the VCXO is shown in Figure 1.16. A VCXO provides the output signal. After audio frequency modulation, it is used to synthesize the microwave signal at 9,192,631,770 Hz, which is then used to excite the hyperfine transition. The detected atomic beam current from the beam tube is applied to a phase sensitive detector using the audio modulation as reference. After interrogations and additional loop filtering, the phase detector input is used to control the frequency of the VCXO. Cesium technology has been optimized for long term timekeeping and frequency reproducibility at the expense of size, weight, power, and warm-up time. A healthy device shows no frequency aging, and the reproducibility is on order of 2E-12 for the life of the cesium tube. The dominant long term noise is random walk frequency, which limits the time keeping to approximately 0.1 micro second per month.

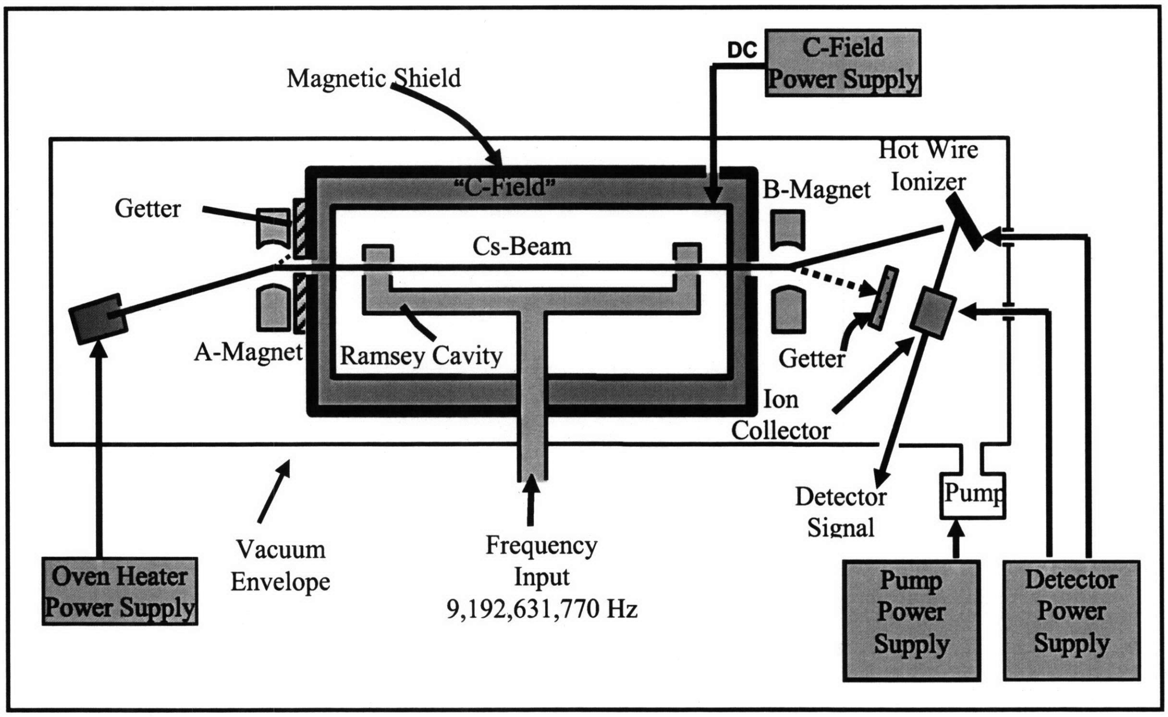

Figure 1.15 Schematic of a Cesium Beam Tube.

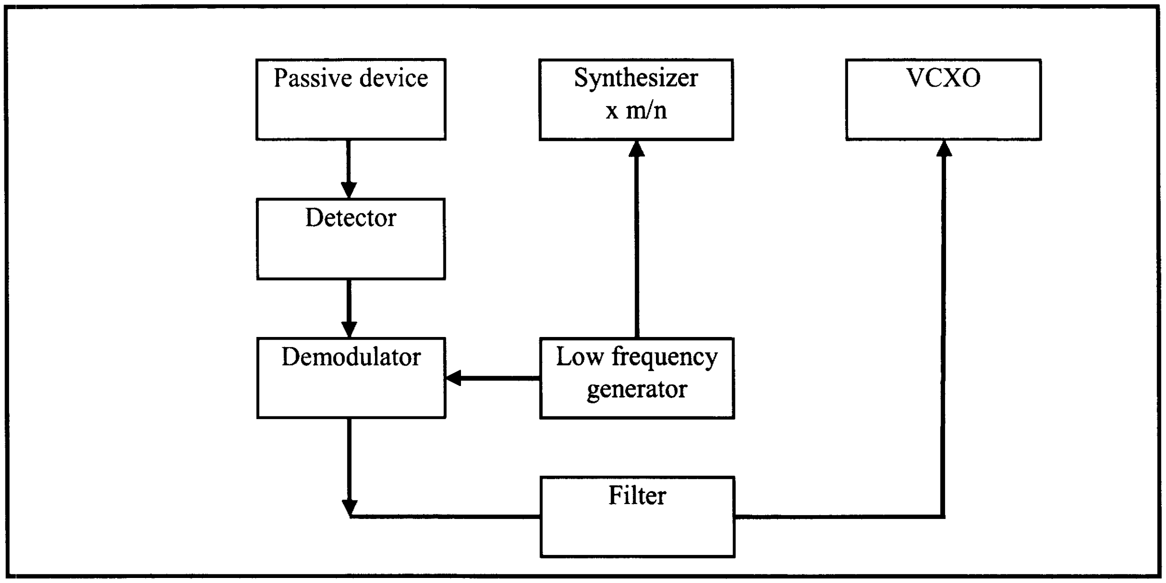

Figure 1.16 Electronic Schematic Showing the Frequency Lock of VCXO to Atomic Resonance.

1.7.3 Passive Hydrogen Atomic Clocks

Charles H. Townes, an American scientist who developed the maser, was not working on an oscillator at all; rather he was seeking a way to amplify microwave radio signals [4]. The resonator in the hydrogen maser is the hydrogen atom, which has, among others, a particular resonant frequency of 1,420,405,752 hertz. Figure 1.17 is a schematic representation of an active hydrogen maser. Unlike cesium and rubidium, hydrogen occurs only in molecular form at room temperature. The 1.42 GHz output from atoms is amplified and mixed with a signal obtained by multiplying the output frequency to the microwave region. A final down conversion of this frequency difference using a reference synthesized from the output frequency completes the conversion of the atomic frequency to baseband. Feedback to the VCXO phase locks it to the microwave signal originating from atoms. Active masers have the best short term frequency stability of all the atomic frequency standards.

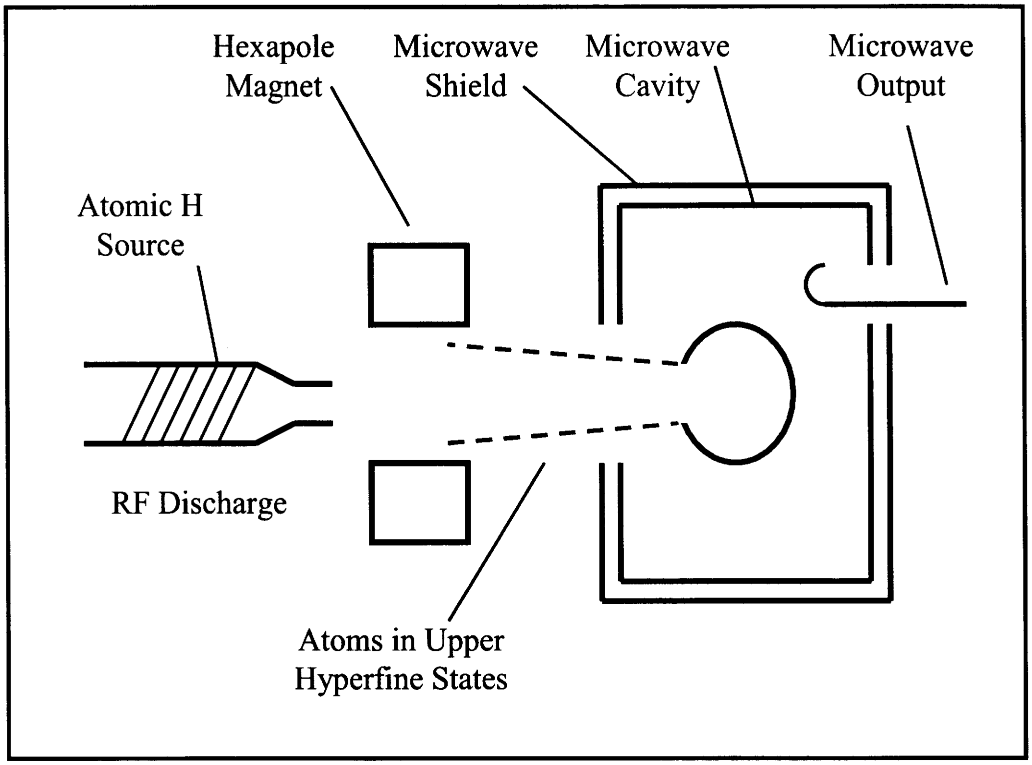

Figure 1.17 Schematic representation of an Active Hydrogen Maser.

Chapter II. Background

2.1 What is a clock?

Time keeping is basically a matter of counting cycles or units of time. The heart of the clock is today, as it was 200 years ago, some vibrating device with a period as uniform as possible [4]. There are two main features in all types of clock (Figure 2.1). The first part of a clock is an oscillating device for determining the length of the second or time interval. This is referred to as the clock's frequency standard, which oscillates at a rate determined by the laws of physics. Historically, the pendulum was the source of time interval. In Pendulum clocks the theoretical frequency is given by:

$$\upsilon = \frac{\sqrt{g/l}}{2\pi} \qquad \text{(Eq. 1)}$$

g=gravitational acceleration

l=length of the pendulum bob's support wire

An ideal pendulum that swings through its lowest point one per second with a frequency of 0.5 Hz will have a length of 99.3621 centimeters if it is operating at sea level and at 45° latitude [9]. A typical wrist watch has as its frequency standard a quartz crystal tuning fork with an oscillation frequency of 32,768 Hz. This number of oscillations is convenient for the associated digital electronic circuit. If this number is divided by 2^{15} by digital chip divider, the result is one cycle per second. The atomic clocks provide a much more accurate frequency that can be generated by any physical device such as a pendulum or quartz crystal oscillator. An atomic clock uses as its reference the oscillation of an electromagnetic signal associated with a quantum transition between two energy levels in an atom. The current official definition of second has been defined as the duration of 9,192,631,770 cycles of the radiation associated with a specified transition of cesium atom in 1967. Frequency is obtained by counting events over 1 second interval.

The second part of a clock is a counter and display which also refereed to as integrator, adder, or accumulator. The counter keeps track of the number of seconds or clock cycles that have occurred [9]. The pendulum counter controls the movements of a system of mechanical levers, gears and wheels that are calculated to drive the second, minute and hour hands in the desired rotation ratios so that they will show the correct time. The basic components of different clocks are illustrated in Figure 2.2.

2.2 What is a Q Factor?

The quality factor or Q factor is a dimensionless parameter that compares the time constant for decay of an oscillating physical system's amplitude to its oscillation period [4]. If there is considerable friction, the resonator will die down rapidly. It means resonators with a lot of friction have a low Q and vice versa. A typical mechanical watch may have a Q of 100; where as atomic clocks have Q's in the millions [4]. One of the apparent advantages of a high-Q resonator is that its resonant frequency does not need to be perturbed with injection of energy [4]. The other advantage of high Q resonator is that it won't oscillate at all unless it is swinging at or near resonant frequency. This feature is closely related to the accuracy and stability of the resonator [4]. Table 2.1 lists the Q factor for various types of clocks.

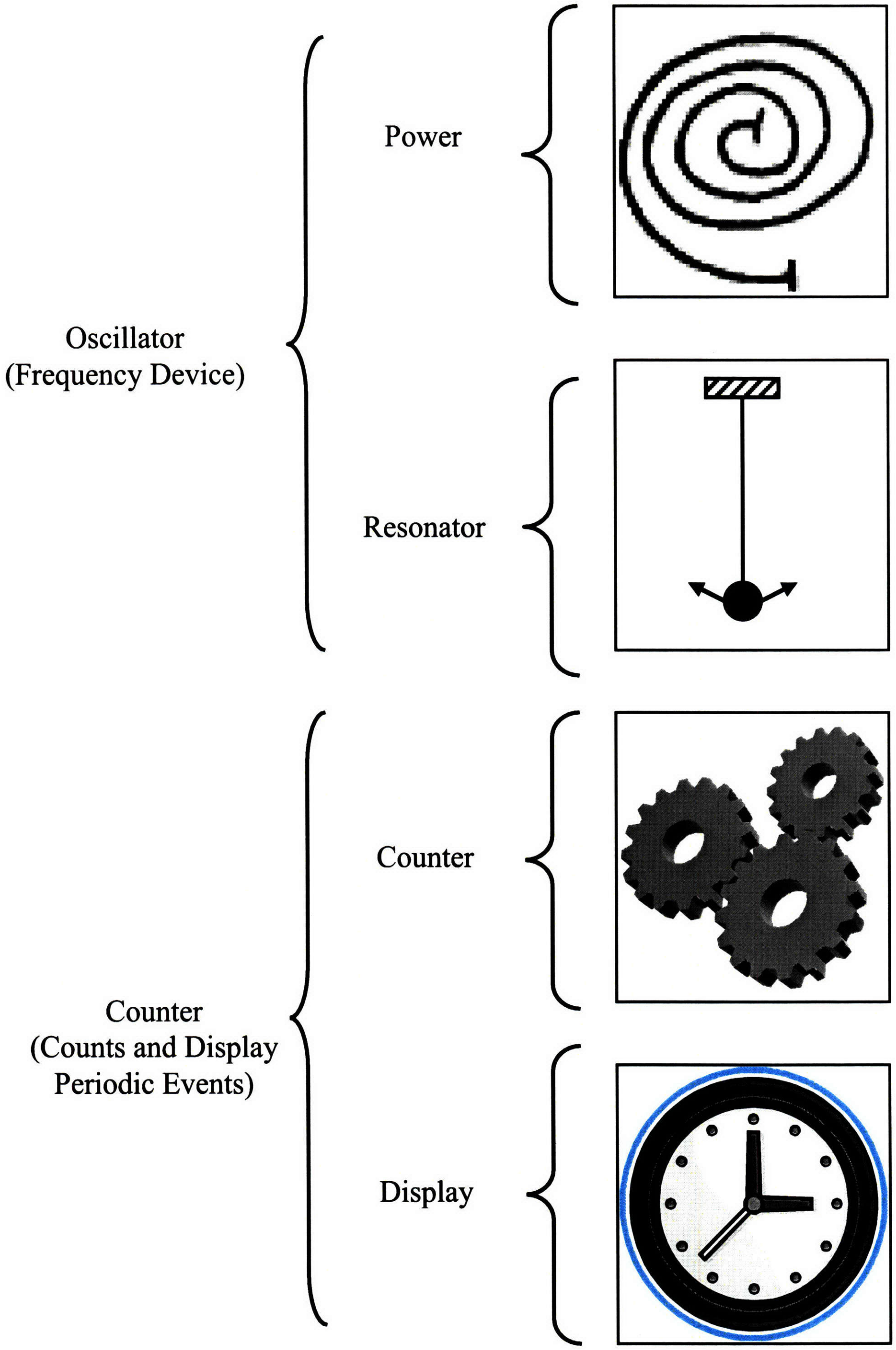

Figure 2.1 What is a clock? An Oscillator and a Counter.

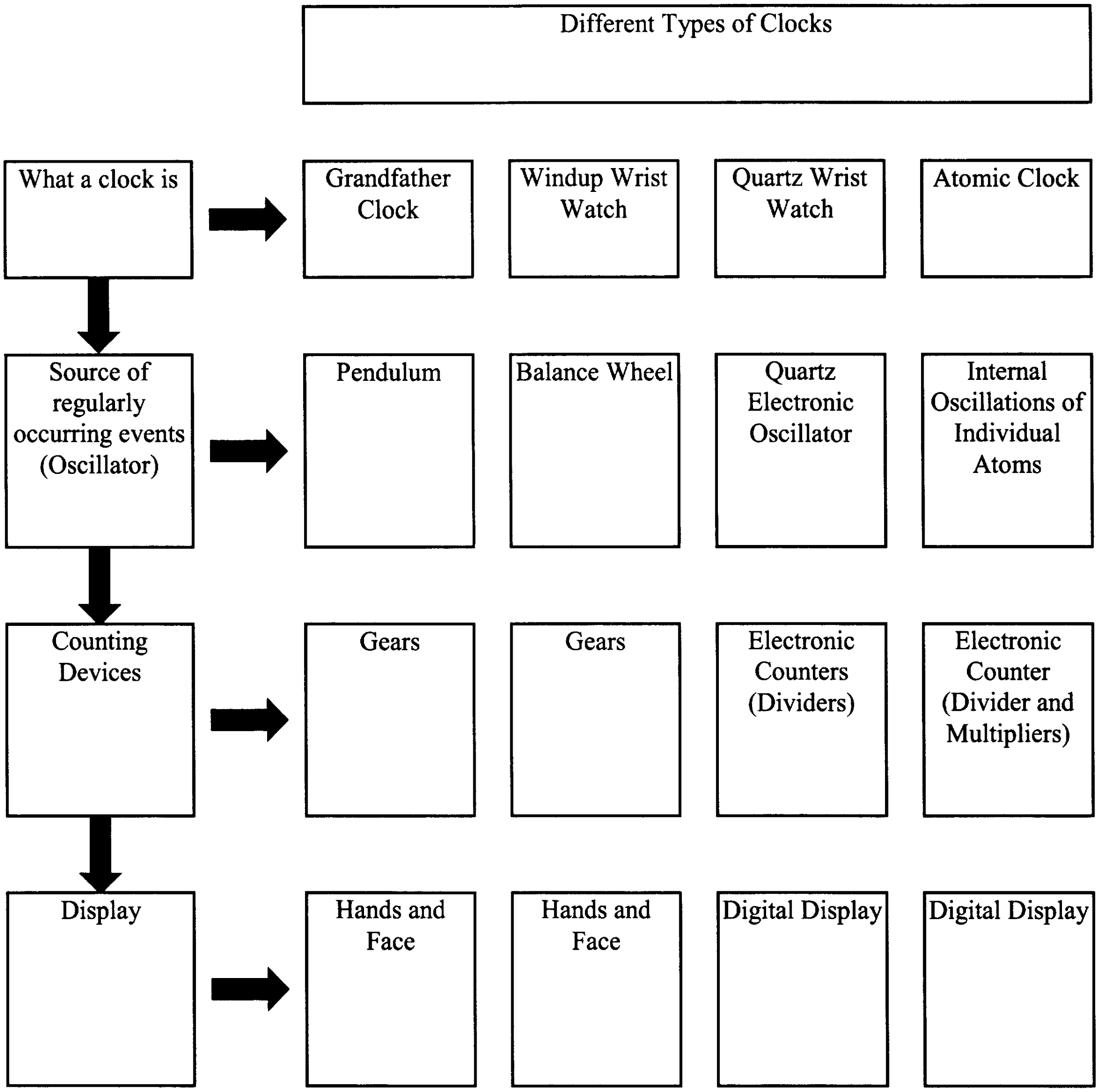

Figure 2.2 Basic Components of Different Clocks.

Table 2.1 The Q factor for Various Types of Clocks.

Types of Clocks	**Q Factor**
Inexpensive Balance wheel watch	1,000
Tuning Fork Watch	2,000
Quartz Clock	10^4-10^6
Rubidium Clock	10^7
Cesium Clock	10^7-10^8
Hydrogen Maser Clock	10^9

2.3 Who needs Time and Frequency?

Time and frequency standards provide three basic types of information: date and time of the day, time interval and frequency [19]. The first type, date and time of the day, indicates when something happened. Date and time of the day is used to record events or to make sure multiple events are synchronized. Without accurate time, our daily lives could not function in an orderly matter. Date information is used to remind us when birthdays, anniversaries and other holidays are scheduled to occur. The time of the day information is used to get to work and school on time. Date and time of the day information have other more sophisticated usage as well. Stock market transactions need to be synchronized so the buyer and seller can agree upon the price at the same time. The TV station has to be ready to receive the network feed from a satellite at the exact instant it arrives. Fighter planes flying in a high speed formation require synchronized clocks. If one fighter plane turns at the wrong time, it could result in a collision. The electric power companies use synchronized clocks throughout their power grids, so the power can be instantly transferred to the parts of the grid where is needed.

The second type of information is time interval [19]. The standard unit of time interval is second (s), which is defined according to a property of cesium atom. However many applications in science and technology require the time interval much shorter than second such as, milliseconds (10E-3 s), microseconds (10E-6), nanoseconds (10E-09 s) and even picoseconds (10E-12 s).

The third type of information is the frequency which is the rate at which something happens. Frequency is as important as time. Accurate frequency control at TV stations means programs are transmitted on the exact frequencies assigned by the Federal communications and Commissions. A T1 high speed internet connection sends data and frequency of 1.544 MHz. When the crystal in quartz watch is oscillated 32,768 times, the watch records that one second is elapsed. All of these applications require an oscillator that produces a specific frequency. The oscillator must be stable over long time intervals.

2.4 Definition of Terms as Applied to Clocks (Oscillators)

There are several useful measures for describing the quality of a clock. A clock's frequency accuracy is how well it can realize the defined length of the seconds. This can be measured by dividing the change in the error of a clock's time by the elapsed time over which the change occurred [9]. The goal of the Harrison chronometers was to have a frequency accuracy of less than three seconds per day, 3/86,400=3.5E10-5. The best primary frequency standards in the world today have the frequency accuracy values less than 1E-14 or one second error every 3 million years.

Frequency stability indicates the change in frequency from one period of time to the next [9]. A clock can have a significant frequency error and still have be very stable. In other words the frequency error stays about the same over time. Two very important kinds of atomic clocks, a hydrogen maser and a cesium beam, are good examples of clocks having different stabilities and accuracies. A hydrogen maser clock has better frequency stability than cesium from second to second or from hour to hour, but not from month to month and longer. On the other hand the cesium beam clock is more accurate than hydrogen maser clock. Quartz oscillators based clocks can very stable for short times, but they drift and age in frequency and don't have the frequency accuracy of atomic clocks. The aging is defined as the change in frequency with time due to internal changes in the oscillator. It is the frequency change with time while factors external to the oscillator such as environment, power supply and etc are kept constant. The Drift, however, is the change in frequency with time that one observes in an application. Drift is due to aging plus changes in the environment and other factors external to the oscillator.

Time accuracy, by definition, means how well a clock agrees with Coordinated Universal time (UTC). NIST provides UTC (NIST), a time scale referenced to atomic oscillators located in Boulder, Colorado [9, 19]. At its source, UTC (NIST) is kept in as close agreement as possible with other national and international standards, typically within a few nanoseconds. There are many cases where what is needed is consistency of time at several locations in s system. For example, the time on GPS differs slightly with UTC. The GPS time broadcast by each of the satellites needs to be synchronized with all of the other satellites in the constellation to within a small number of nanoseconds in order for the system to work properly. This is achieved for GPS by presence of atomic clocks on board the satellites [20]. The telecommunication industry is another classic example. In order to transfer the large amount of data among many network nodes, the nodes need to be synchronized or the data will be lost or the transmission will be faulty [19].

Time stability is usually correlated with frequency stability and is a useful as a measure of change with respect to some uniform of time distribution systems. In a hierarchy of calibrations at the top of the pyramid are the primary reference standards. To determine their accuracy, some primary frequency standard are taken through a series of measurement cycles to obtain a best estimate of the second [9].

Chapter III. Methods

3.1 Past Technologies

The Egyptians in 1500 B.C had developed portable shadow clocks, or sundials, which used the shadow of sunlight to indicate time. The sundials could not be used on cloudy days or at night.

In 1500 B.C The Egyptians also developed the water clocks. Water clocks were among the first timekeepers that didn't depend on the observation of other planets. Water clocks in contrast to sundials worked day and nights but were big and awkward and they were not portables. In water clock the water flow rate was very difficult to regulate, it did not keep very good time and often froze in western European winter.

Sand clocks were introduced in the 14th century to avoid the freezing problem. Sand clocks were limited to measure short time interval due to the weight of the sand.

The first mechanical clock came to use came into use sometime around 1285. These mechanical clocks had a verge and foliot, which were used for the mechanism that sounded a bell. These clocks could measure time for a long period of time but were not keeping accurate time and no two clocks were showing the same time. Variations of the verge and foliot mechanism reigned for more than 300 year. The period of oscillation of escapement depended heavily on the amount of driving force, the amount of friction in the drive and the skills of the craftsman. Like water flow, the rate was difficult to regulate. This invention is important in the history of technology, because it made possible the development of all-mechanical clocks. This caused a shift from measuring time by continuous processes, such as the flow of liquid in water clocks, to repetitive, oscillatory processes, such as the swing of pendulums, which had the potential to be more accurate.

Galileo Galilei is credited with first realizing that the pendulum could be the frequency-determining device for a clock as early as 1582. In 1656, Christiaan Huygens made the first pendulum clock, regulated by a mechanism with a natural period of oscillation which greatly increased the accuracy of time measurement. His early clock had an error of less than 1 minute a day, far more accurate than any previous timepiece. His later refinements reduced his clock's error to less than 10 seconds a day. The pendulum clocks worked day and night and were more accurate but were also big and awkward.

In 1714 The British government had a need for a new clock with the goal of 3 seconds per day accuracy for safer navigation; three times better than available clocks. Harrison responded to this need and designed the chronometer within the specified specifications that made navigation practical. The accuracy of his chronometer was about 1 second per day. One of Harrison's chronometers gained only 54 seconds during five month voyage to Jamaica or about one third second per day. The rhythm of Harrison's chronometer was maintained by the regular coiling and uncoiling of a spring. These types of clocks are more portable than pendulum's clock.

The concept of need, goals and what drives a function in system architecture framework is shown in Figure 3.1 [21]. Figure 3.2 represents Object Process Diagram (OPD) for a need of accurate chronometer for safe navigation. OPM in recent years has emerged as an increasingly popular graphical and formal language for representing product architectures [21, 22].

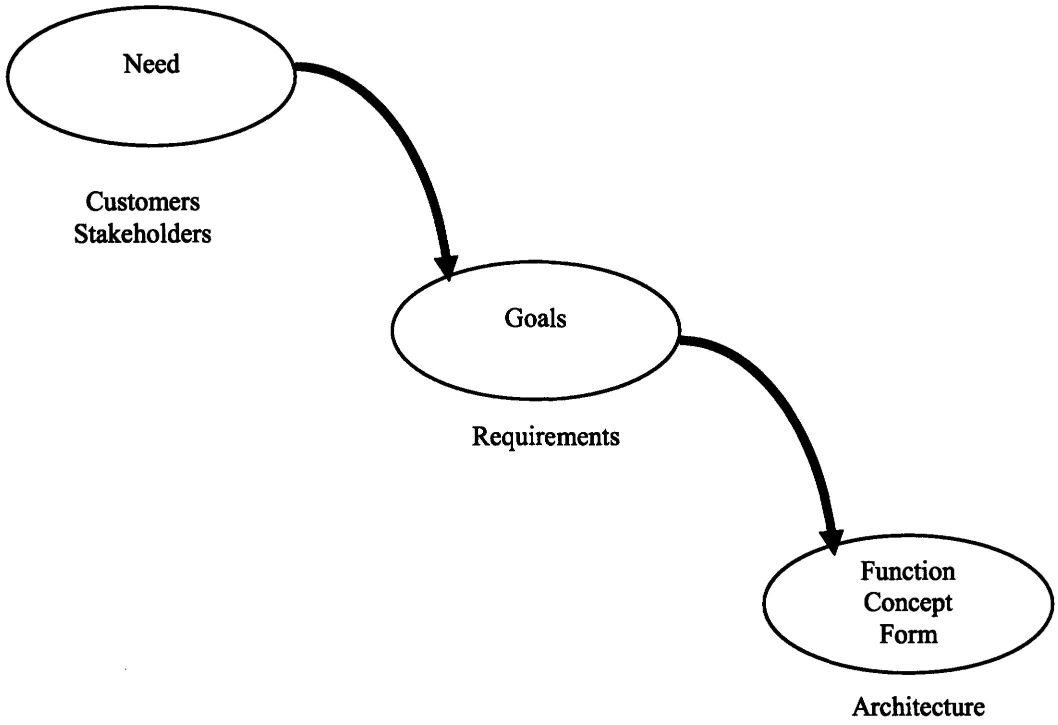

Figure 3.1 What Drives a Function? Framework of System Architecture [21].

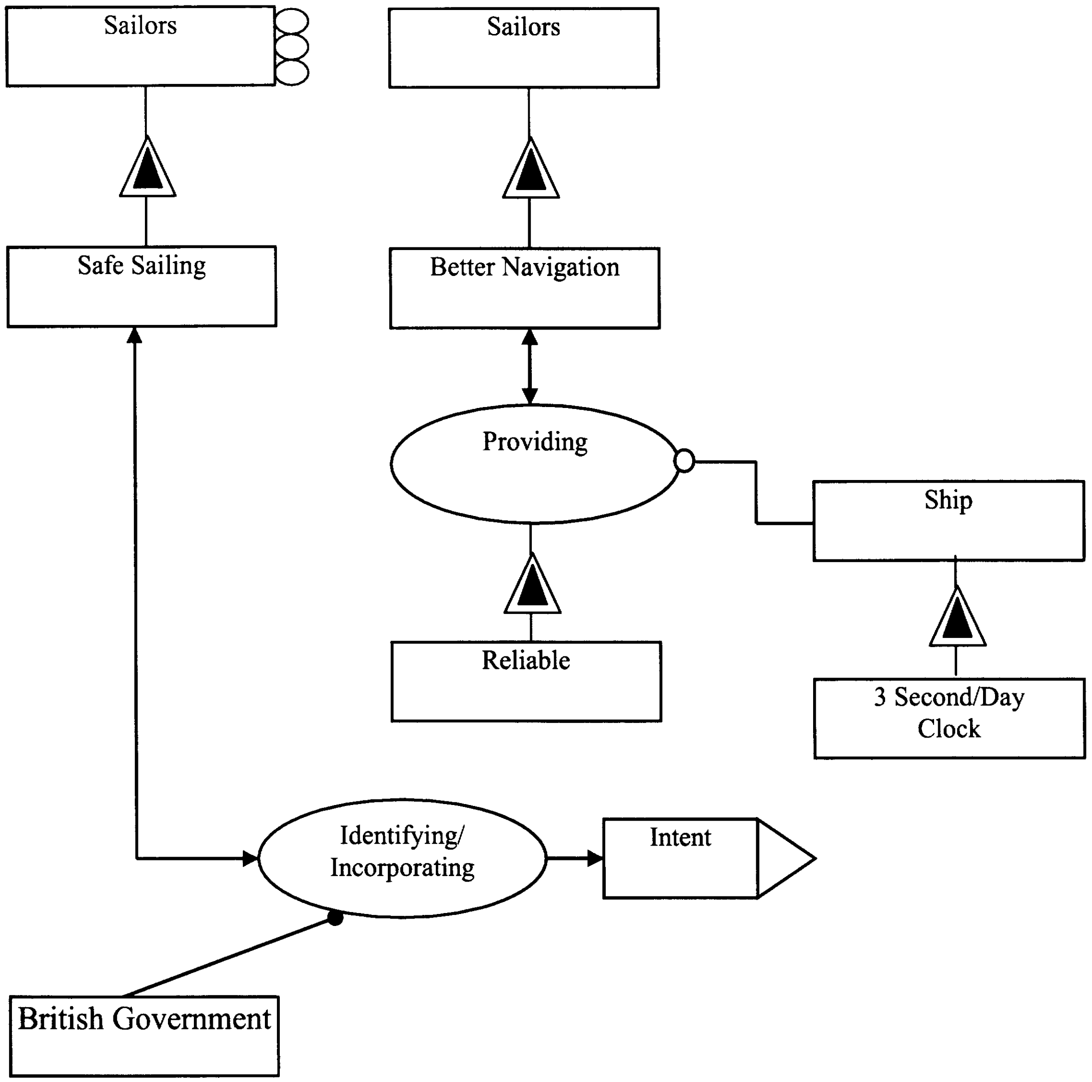

Figure 3.2 Object Process Diagram (OPD) of Clock Requirement for Navigation.

The introduction of the pendulum and Harrison's chronometer was a giant step in history of keeping time. The clock with two pendulums, developed by Shortt in 1931, squeezed just about the last drop of perfection out of mechanical clock. A new approach was needed to improve the accuracy of the clocks.

In the early 20th century, as radio broadcasting stations matured and telephone wires carried more message, maintaining stable electrical frequencies and planning to monitor the frequencies became critical technical problems. Figure 3.3 represents Object Process Diagram (OPD) for a need of frequency standards for telecommunication and radio broadcasting applications. In 1927 the first quartz clock was built by Warren Marrison and J.W. Horton at Bell Telephone Laboratories in response for the need of reliable frequency standards.

The quartz clock itself did not provide a new definition of the second. However, the quartz precision helped scientists identify irregularities in Earth's rotation and show the earth was not reliable baseline for time keeping. The reason that quartz clocks did not redefine the second is that the oscillations, or vibrations, of quartz crystals begin to drift over a long period. The new second would have to wait for the emergence of the atomic clock. The development of radar and extremely high frequency radio communications in the 1930s and 1940s made possible the generation of the kind of electromagnetic waves needed to interact with the atoms. These new development led to the discovery of atomic clocks. In 1967, it was agreed by 13th General Conference of Weights and Measures (CGPM) that: "The second is duration of 9,192,631,770 period of radiation corresponding to the transition between the two hyperfine levels of the ground state of cesium-133 atom [9, 19]. Figure 3.4 summarizes the evolution of the clocks.

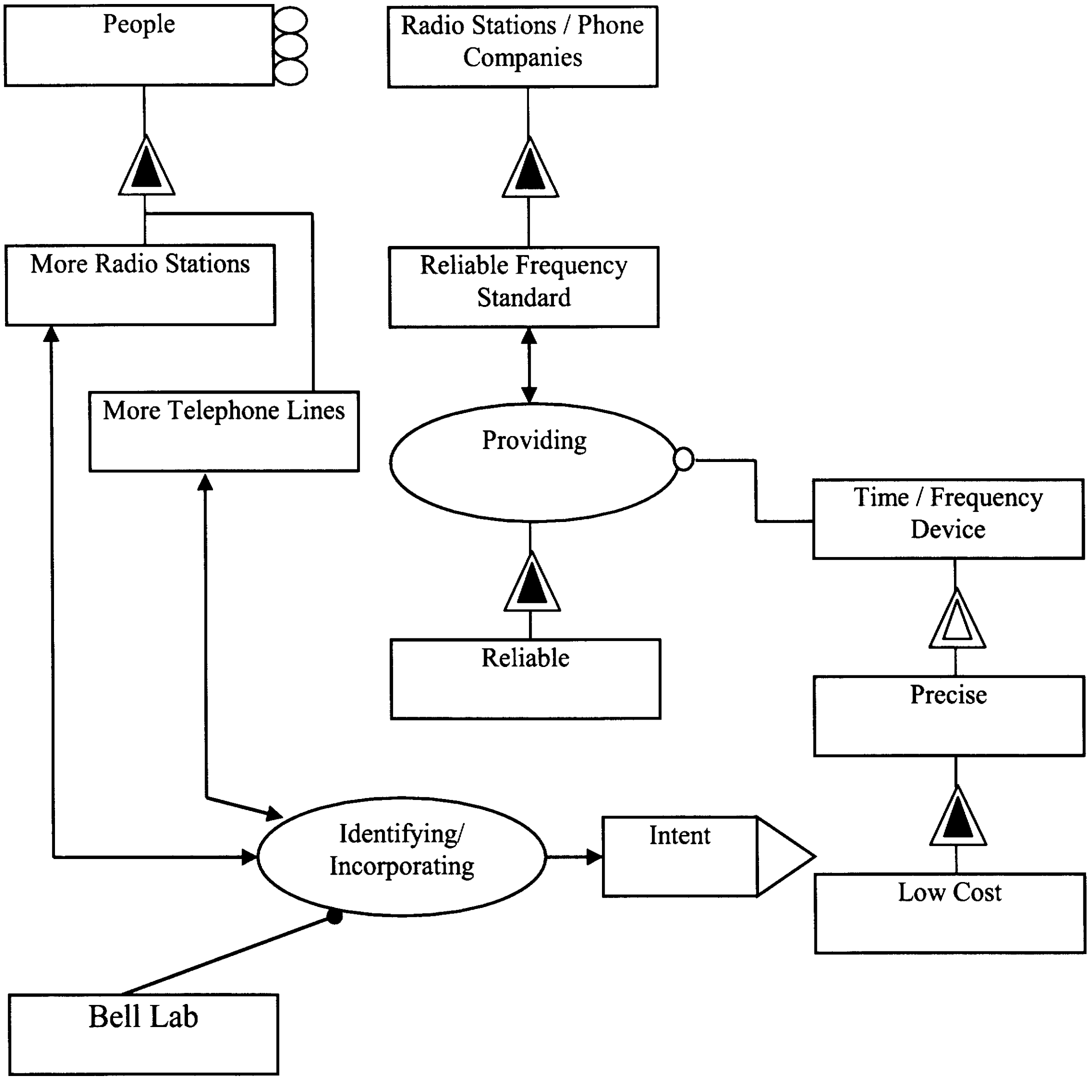

Figure 3.3 Object Process Diagram (OPD) of a Need for Frequency Standard.

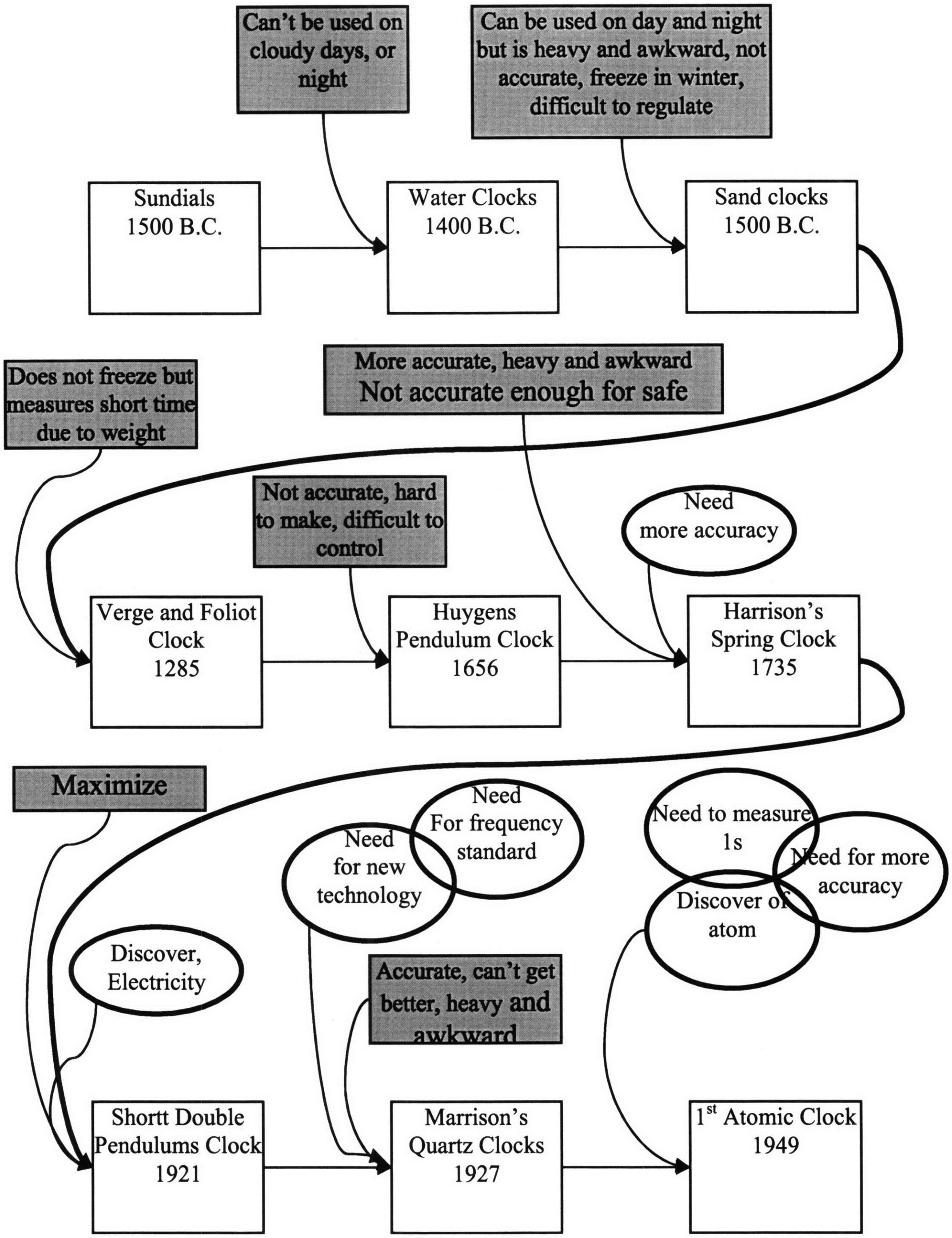

Figure 3.4 Analyzing the Evolution of the Clock Development.

3.2 Present Technologies

3.2.1 Quartz Crystal Oscillator

The quartz oscillators are in close competition with low end rubidium atomic clocks in telecom applications. The advantages of present commercial quartz oscillators are lower cost, small size, light weight, lower power consumption, low phase noise and high MTBF. Although there appear to be cost advantages for the hardware, when coupled with calibration intervals that are more frequent than rubidium atomic oscillators, the cost advantage over rubidium is questionable in most applications. One of the important characteristics of quartz crystal oscillators is that they can exhibit very low phase noise. In a crystal oscillator, the crystal mostly vibrates in one axis. Therefore, only one phase is dominant. This property of low phase noise makes them particularly useful in some telecommunication applications where stable signals are required. For a system in which cost, size, weight, and power consumption are most important, and where aging and retrace disadvantages can be tolerated, the quartz oscillator is the proper choice. If rapid warm up is needed and the equipment will be operated in a hostile environment, these advantages may be negated. Due to aging, slow warm up and environmental factors such as temperature and vibration, it is very difficult to keep even the best quartz oscillators within one part in 10E-10 of their nominal frequency without constant adjustment. For this reason, atomic oscillators are used for applications that require better long-term stability and accuracy. There are many quartz crystal oscillator manufacturers in the world.

Some companies have been very successful by developing higher cost, higher performance quartz oscillators to compete with low end rubidium oscillators in the markets that is more cost sensitive than performance sensitive [Figure 3.5]. The Rubidium manufacturers in order to compete are closing the gap on cost by developing lower cost and lower performance rubidium oscillators for the same market.

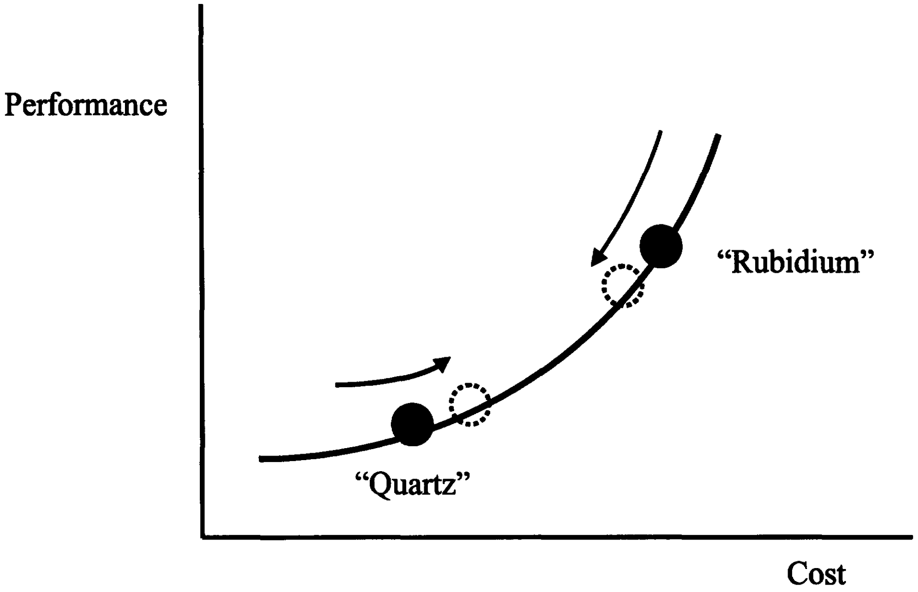

Figure 3.5 Two Competitors: Different Positions on Same Production Frontier.

3.2.2 Rubidium Atomic Clocks

Rubidium atomic clocks provide enhanced accuracy, stability and timing precision compared to quartz-based technologies The advantages of present rubidium oscillators are small size and light weight, medium power requirements, extremely fast warm up and low cost. These advantages, coupled with good performance in hostile environments, make the rubidium oscillator the first choice for commercial ground, mobile, telecom and military tactical systems. It has no major disadvantages except aging of parts in 10E-10 per year. A high performance Rubidium oscillator has the better short term stability than the standard cesium tube oscillator from 1 second to 10,000 seconds Alan variance. The majority of rubidium oscillators are used in telecom applications.

There are about 8 rubidium atomic clock manufacturers in the world. Table 3.1 lists the manufacturers of rubidium atomic clocks worldwide. Figure 3.6 illustrates the basic architecture of an atomic clock, decomposed into assemblies (modules), as well as value delivering function (performance) in OPD.

Table 3.1 Worldwide Manufacturers of Rubidium Atomic Clocks

Company	Location	Commercial (C) Military (M) Space (S)	Production Volume
Symmetricom Efratom→Ball→Datum→Symmetricom	United States	C, M, S	High
KernCo	United States	No Data	No Data
FEI Litton→FEI	United States	C, M, S	Medium
PerkinElmer Varian→General Radio→EG&G→ PerkinElmer	United States	C, M, S	Low
Stanford Research System	United States	C	Low
Fujitsu	Japan	C	Low
Accubeat Tadiran→Accubeat	Israel	C, M	Low
SpectraTime Temex→SpectraTime	Switzerland	C, S	Low
Quartzlock	Russia	C, M	Low

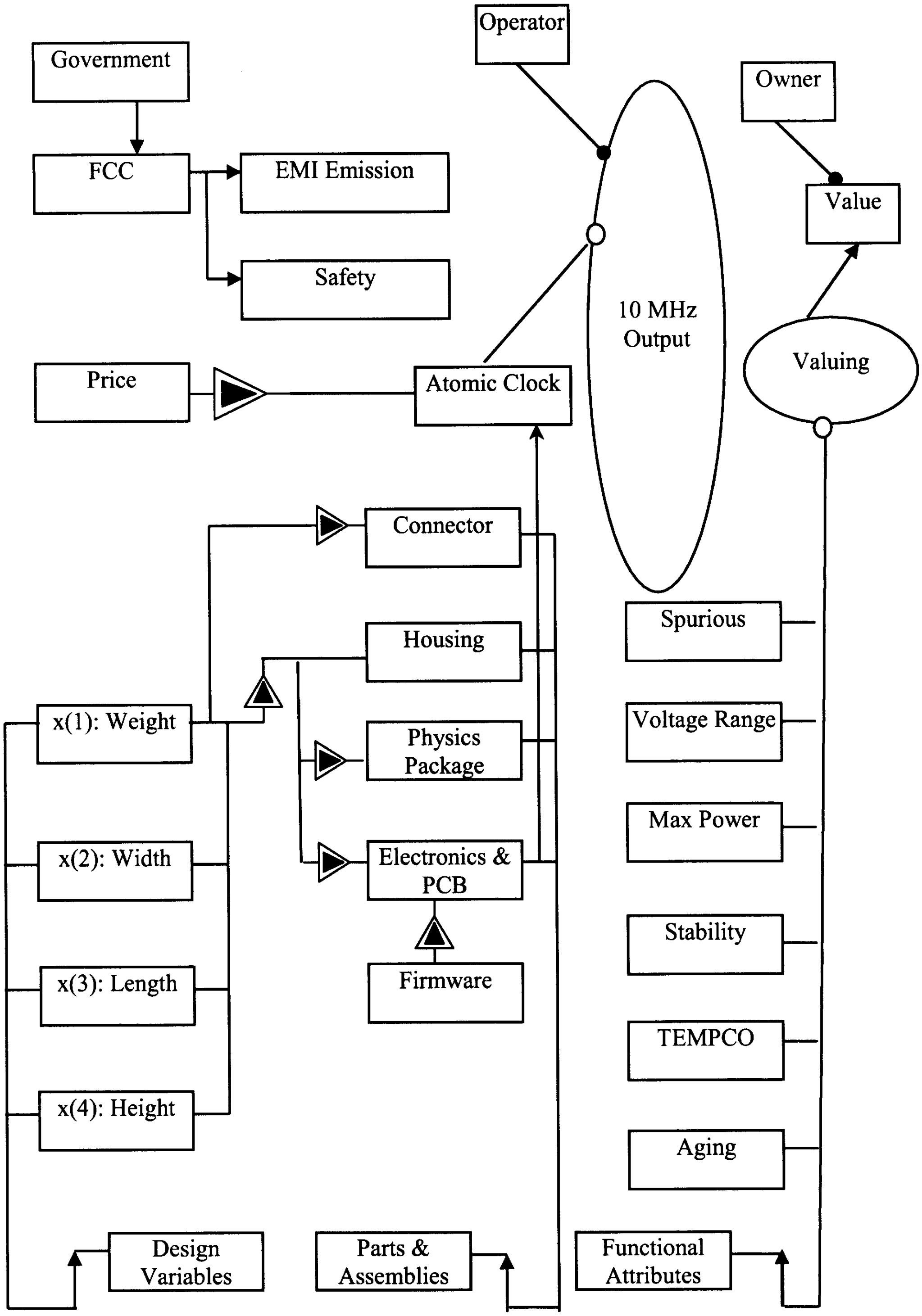

Figure 3.6 Object Process Diagram (OPD) of an Atomic Clock.

3.2.3 Cesium Atomic Clocks

A cesium atomic clock is the most accurate realization of a reference time unit that mankind has yet achieved. In 1967, the 13th General Conference on Weights and Measures first defined the second, in terms of atomic time rather than the motion of the Earth. A second was defined as the duration of 9,192,631,770 cycles of microwave light absorbed or emitted by the hyperfine transition of cesium-133 atoms in their ground state undisturbed by external fields. Symmetricom is the sole source of manufacturing commercial cesium atomic clock in the world.

The advantages of cesium atomic clock are excellent long-term stability from 10,000 seconds and longer, with no aging. The large size, weight, higher power, and cost make the cesium atomic clock more useful in stationary and benign environmental applications, including providing a reference against other, less stable oscillators that periodically require checking and error correction. Cesium's frequency has now been harnessed as the time standard for the atomic clocks aboard GPS satellites. Rubidium clocks ride along as redundant standards.

There has not been any major work on redesigning the cesium atomic clock for the last 30 years. Figures 3.7, 3.8 and 3.9 show the pictures of three types of Cesium clocks manufactured by Symmetricom.

NIST and other organizations are collaborating on research projects to develop Optically Pumped Cesium (OPC) standards. The proper atomic energy levels are populated by optical pumping with the use of laser diodes (see Figure 3.10). Optical pumping provides superior utilization of cesium atoms, and provides the potential advantages of higher signal to noise ratio, longer life and lower weight.

Figure 3.7 5071A Primary Frequency Standard (Symmetricom).

Figure 3.8 Cs4000 Cesium Frequency Standard (Symmetricom).

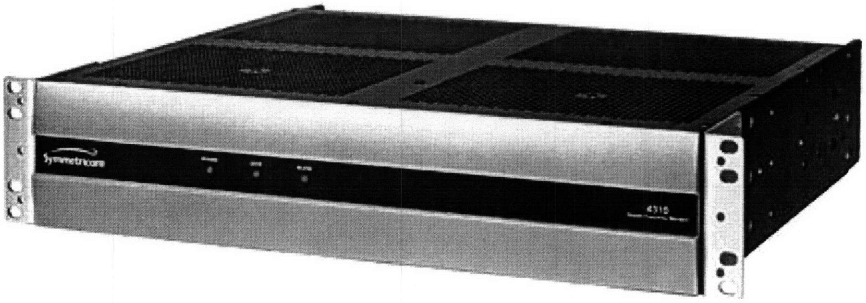

Figure 3.9 CsIII Cesium Frequency Standard (Symmetricom).

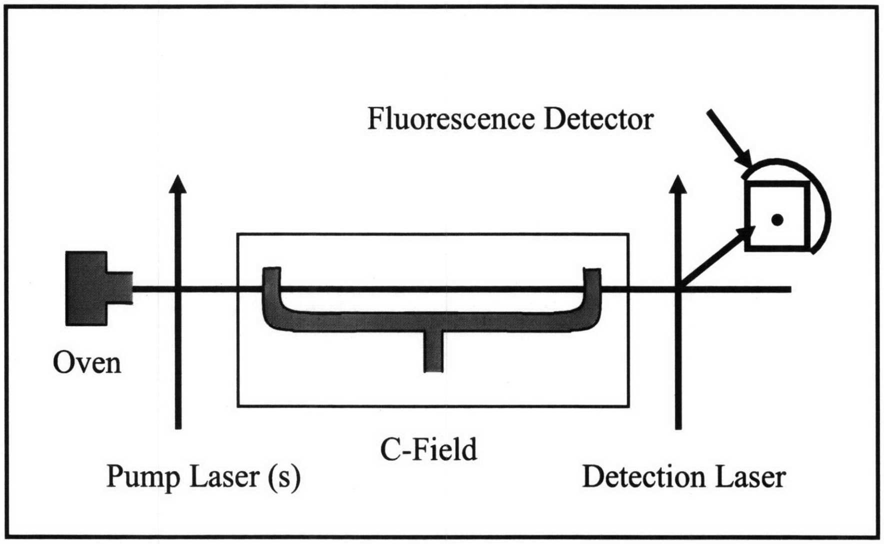

Figure 3.10 Essential Elements of an Optically Pumped Cesium Beam Standard.

3.2.4 Hydrogen Masers Atomic Clocks

The advantages of hydrogen masers are extremely high short and long term stability even better than the best cesium atomic clocks. The maser's large size, weight, power requirements, and medium tolerance of hostile environments (and very high cost) relegate it to a more stationary environment. It is good choice in cesium atomic clock applications where the short term performance of cesium is inadequate. The U.S. Naval Observatory (USNO) currently maintains 20 hydrogen maser frequency standards at which 13 have been in use for multiple years. The USNO uses a combination of hydrogen maser frequency standards and commercial cesium standards to create its timescale [23]. Hdrogen masers are being used by Paris Observatory, US Naval Observatory (USNO), National Institute of Standards and Technology (NIST), National Physical Laboratory (NPL) in England, US National Radio Astronomy Observatory, Johns Hopkins Applied Physics Laboratory, Shanxi Astronomical Observatory in China, SP Swedish National Testing and Research Institute, Instituto Elettrotecnico Nazionale in Italy, Instituto y Observatorio de la Armada in Spain, Korea Research Institute of Standards and Science, Shanghai Astronomical Observatory, Urumqi Astronomical Observatory in China, Arecibo Observatory in US and others [24]. There are about 5 commercial manufacturers of the Hydrogen maser in the world. The list of manufacturers are listed in Table 3.2. Figures 3.11-3.15 show a few types of hydrogen masers developed by different manufacturers around the world.

Table 3.2 Worldwide Manufacturers of Hydrogen Masers

Company	Location	Production Volume
Symmetricom	United States	Very Low
T4 Science	Switzerland	Very Low
Vremya	Russia	Very Low
Kvarz	Russia	Very Low
Anritsu	Japan	Very Low

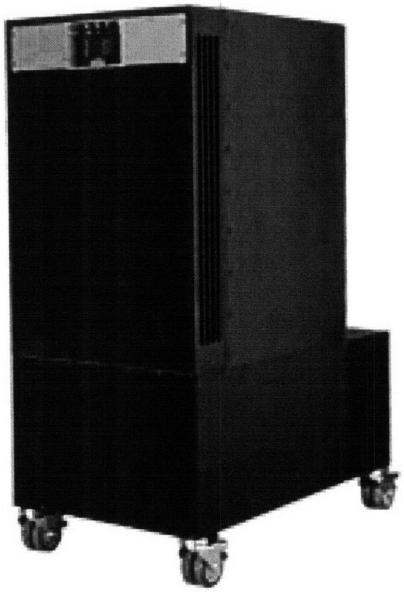

Figure 3.11 MHM 2010 Active Hydrogen Maser (Symmetricom).

Figure 3.12 The CH1-75 Active Hydrogen MASER (Kvarz).

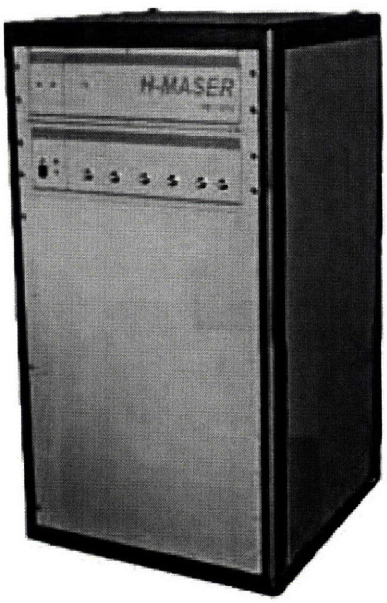

Figure 3.13 Active Hydrogen Frequency Standard VCH-1003A (Vremya).

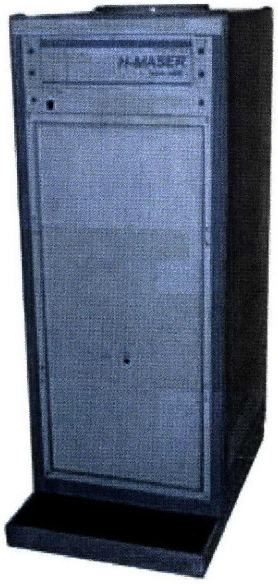

Figure 3.14 Active Hydrogen Frequency Standard VCH-1005 ((Vremya).

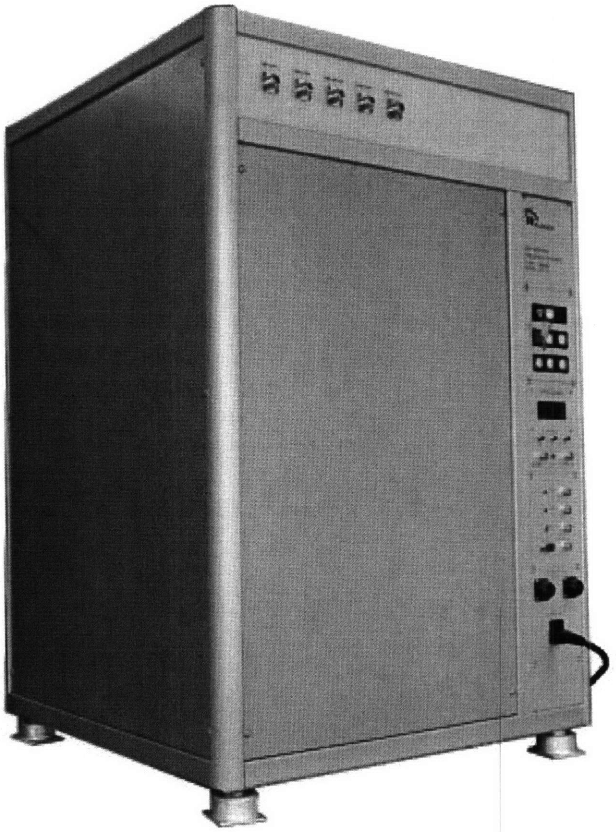

Figure 3.15 iMaser, Active Hydrogen Maser (T4 Science).

The specifications and important considerations for each of the oscillator are shown in Table 3.3.

Table 3.3 General Comparison of High Performance Oscillators.

Description	**Quartz Oscillator**	**Rubidium Oscillator**	**Commercial Cesium Beam**	**Hydrogen Maser**
Primary Standard	No	No 6.834,682,613 GHz	Yes 9.192,631,770 GHz	No 1.420,45,751 GHz
Fundamental Wear out Mechanism	None	None Rb Lamp life (20 Years Plus)	Yes Cs Beam Tube (7 Years Plus)	Yes Ion Pumps & H_2 Source Depletion (7 Years Plus)
Portability, Application	Extremely Portable	Very Portable	More Ground and Lab Oriented	Definitely More GRD. And Lab Use
Approx. Size	1.3"X1.3"X1.3"	3.5"X3"X0.7"H*	21"DX17"WX6"H**	30"DX18"WX42"H***
Approx. Weight	0.09-2 Lbs	0.55 Lb*	66 Lb**	475 Lb***
Approx. Power	0.3-5W	5-18W*	45W-85W**	75-150W***
Approx. Cost	$0.2K-2K	$1K-10K	$30K-60K	>$200K
Short Term Stability, t=1s	1 to 5E-13	2E-12 to 3E-11	5E-12**	2E-13***
Aging/Day	1E-11 to 5E-10	3E-13 to 1E-12	None	2E-16***
Accuracy/Year	1E-07	1E-10 to 1E-09	Parts in 10E-13	Parts in E-12
Retrace	Parts in E-9	~1.5E-11	Parts in E-13	Better than 3E-13
Warm up Time	10-60 mins Parts in E-08	3 to 10 mins Parts in E-10	30 mins Parts in E-12	24 hours ~1E-12

3.3 New Technologies

3.3.1 The Chip-Scale Atomic Clock

The Defense Advanced Research Projects Agency (DARPA) is the central research and development organization for the Department of Defense (DoD). It manages and directs selected basic and applied research and development projects for DoD, and pursues research and technology where risk and payoff are both very high and where success may provide dramatic advances for traditional military roles and missions.

In 2002 DARPA initiated a competitive call for proposals to demonstrate the feasibility of Chip Scale Atomic Clock (CSAC). Symmetricom led a development team, which included Draper Laboratory and Sandia national laboratories, that was awarded the contract to investigate, theoretically and experimentally, the feasibility of very small atomic clock using cesium (chip scale) [25].

The collaboration with DARPA developed the CSAC (see Figure 3.16), which is one hundred times smaller and lower power than any existing atomic clock technology (could run on a AA battery) [25].

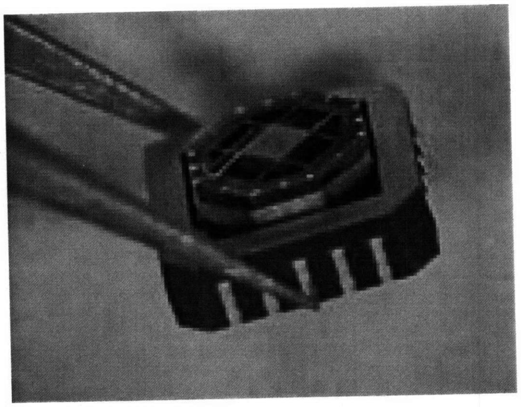

Figure 3.16 Chip Scale Atomic Clock.

The CSAC incorporates passive, vapor-cell references based on coherent population trapping (CPT). CPT is a nonlinear phenomenon in atoms in which coherences (electromagnetic multipole moments) between atomic energy levels are excited by pairs of optical fields. Because the CPT technique does not require a microwave field, it is possible to design and build frequency references far smaller than would ordinarily be possible with direct microwave excitation.

3.4 What's Next?

Both Hydrogen maser and cesium atomic clocks are mature products whose designs have not changed for the last 30 years. The demands for cesium and hydrogen maser are low, but steady and products are expected to remain consistent, with little or no price change. Continuous improvement initiatives are ongoing to lower the manufacturing cost and replace the obsolete components.

In contrast to cesium standards and hydrogen masers, the demand for rubidium atomic clocks and high performance quartz oscillators are very high and increasing in telecom communities, with customers demanding lower and lower cost. This market is large enough to support continuing technological innovation.

Figure 3.17 represents the evolution of rubidium atomic clocks towards low cost, small and lower power consumptions from 1980 to present.

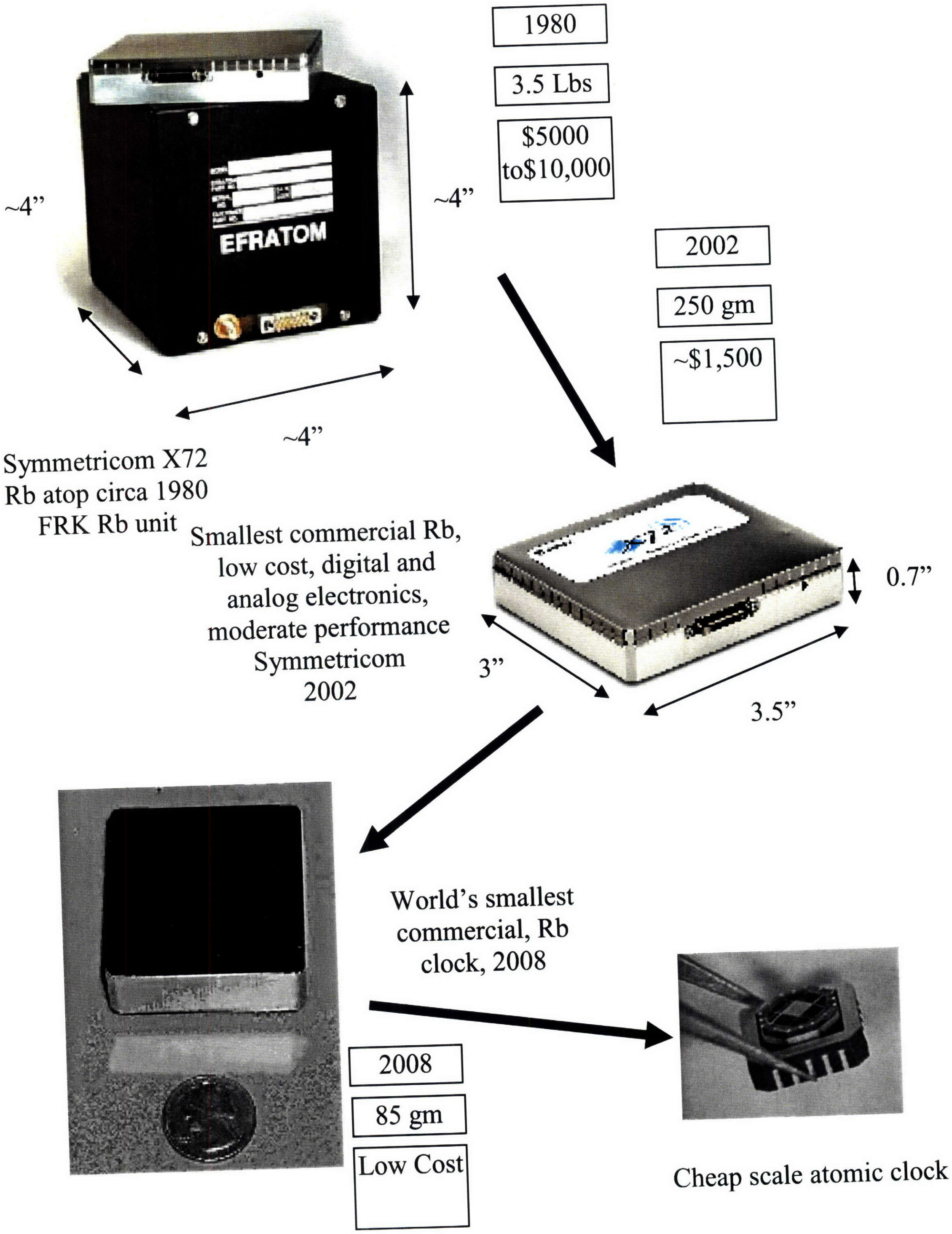

Figure 3.17 Evolutions of Rubidium Atomic Clocks [Symmetricom]

The world's first commercially available miniature clock in 2008 marks a major step toward in the evolution of rubidium atomic clocks [26]. This product has been designed to be suitable for applications requiring compact design, lower power consumption, and excellent aging and precision in an economical and easily adaptable package. This is a major breakthrough since the innovation of Rubidium atomic clocks and is based on coherent population trapping (CPT) as discussed in previous section.

This miniature clock has the physical dimension of 2"X2"X0.7" and consumes minimal power, operating over a wide range of temperatures [26]. This product is targeted for applications where an economical solution for frequency stability is required, such as wireless applications.

It is predicted that the future of rubidium oscillators will be based on CPT technology. Future rubidium clocks will be smaller, cheaper, and will be operated by small batteries.

Chapter IV. Discussion and Conclusions

An atomic clock uses the resonance in the hydrogen, cesium, or rubidium atom as the basis for the stability and accuracy of reference signal. Atomic clocks play an essential role in the precise timing and synchronization of modern communications and navigation systems. The accuracy and stability of atomic clocks are the key determinants for the performance of command, control, communications, and intelligence for U.S. military. Without atomic clocks navigation, surveillance, electronic warfare, missile guidance and identification would not be possible. The atomic clock provides essential solutions to a large number of industries and organizations. In time keeping and metrology applications, these clocks are the official standards. Without these clocks utility companies would not be able to realize the accurate measurement and control of energy allocation. Telecommunications systems are dependent on precise time references for quality of service.

A cesium atomic clock is the most accurate reference unit that has yet been achieved. The commercial cesium atomic clock is very mature, and the demand for this type of clock is expected to be flat. Symmetricom is the only company that manufactures cesium clocks.

A size reduction is possible due to new physics improvement by using optical pumping techniques, but no major changes in performance and prices are expected. Primary frequency standards will probably be based on optical transition in next decade.

The hydrogen maser is very mature product (like cesium) and the design has remained the same for the last 30 years. The demand for this product is very low and there are not many competitors in this market. Masers outperform the high performance cesium clocks for a time period of sub seconds to one day. Hydrogen masers still will be used in national labs, observatories and European satellites. Continuous improvement is ongoing to lower the manufacturing cost and replace the obsolete components. Maintaining viable part availability for a 30-year old product remains a challenge.

Rubidium atomic clocks provide enhanced accuracy, stability and timing precision compared to quartz-based technologies. Until now, the size cost and power consumption of existing atomic clock technologies have exceeded that of quartz-based clocks. The world's first commercially available miniature in 2008 marks a major step toward in the evolution of rubidium atomic clocks [27]. It is predicted that future of rubidium oscillators will be based on coherent population trapping technology. The miniature rubidium clocks will be smaller, cheaper, and will be operated by small batteries.

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