TIME AND FREQUENCY ACTIVITIES AT SP IN SWEDEN

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Abstract

The national time and frequency laboratory of Sweden has since 1995 been a part of the measurement technology department at the SP Technical Research Institute of Sweden. The laboratory is responsible for maintaining a realization of Swedish standard time and the dissemination of this time scale in Sweden. The objective of the laboratory is to support and supply Swedish industry and authorities with accurate measures of time and frequency by instrument calibration, knowledge transfer, time dissemination, and research and development. Swedish standard time is connected by law to UTC as maintained by the BIPM. UTC (SP) is the realization of UTC in Sweden and is traceable to UTC via BIPM and time transfer using the GPS and TWSTFT techniques.

This paper describes the generation and maintenance of UTC (SP) and the equipment, including clocks and time transfer equipment, needed for this task as well as the concept of a "Distributed Time Scale" using alternate versions of UTC (SP) maintained at sister laboratories in Sweden. The paper presents also activities related to the dissemination of Swedish standard time including GPS time transfer, Network Time Protocol (NTP), telephone time code, and a speaking clock. Finally, research activities including time transfer in optical fiber networks, continuous GNSS carrier-phase processing, and Kalman-filter-based ensemble clock generation are briefly presented.

INTRODUCTION

SP Technical Research Institute of Sweden is a government-owned but independent research institute with a wide range of research fields: construction, microbiology, biotechnology, chemistry, and energy technology, to name a few areas. SP and its subsidiaries employ more than 900 people. The Time and Frequency laboratory is part of the Measurement Technology department that realizes most SI units such as meter, kilogram, ampere, and, of course, the unit of time, the second. The Time and Frequency laboratory is relatively young on an international scale. Up until summer 1995, Swedish Metrological time and frequency activities were carried out by Telia in Stockholm, at that time a state-owned Swedish Telecommunication Company. During the last 14 years the time and frequency laboratory has evolved from one person with one cesium clock and a single-channel GPS-receiver in 1995 to a team of six colleagues and a multitude of equipment and competence of today. Now SP commits about 20 clocks to

TAI and is active in the development of new time transfer techniques.

DISTRIBUTED SWEDISH TIME-KEEPING

SP Time and Frequency currently has two sister laboratories at independent organizations where SP has placed equipment and maintains time scales closely related to UTC (SP). Internet communication between the sites glues the Swedish time keeping together and forms a redundant and self-retained distributed structure (see Figure 1). The two sister laboratories are:

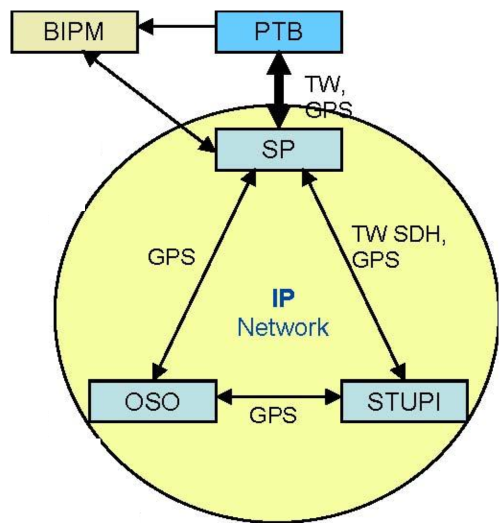

Figure 1. Time links between Swedish timekeeping sites.

1) STUPI AB **[1]**, Svensk TeleUtveckling & ProduktInnovation AB, is a company heavily involved in Internet technology development. As a nonprofit activity, STUPI is also committed to the development of robust national timekeeping and distribution of time and frequency within Sweden. The laboratory is placed in central Stockholm with excellent network communication capabilities and provides a free-of-charge NTP service.

2) Onsala Space Observatory (OSO) **[2],** affiliated with the section of Radio and Space Science at Chalmers University of Technology in Gothenburg, is the Swedish National Facility for Radio Astronomy. It operates an mm-wave radio telescope for use in VLBI astronomy and geophysics. Due to its requirements for stable frequency references, the observatory is a natural place for timekeeping.

EQUIPMENT AT SP

The clock ensemble at SP consists of (see Figure 2):

- Active hydrogen maser SigmaTau MHM2010 (216) 407201
- Active hydrogen maser CH1-75A 407203
- Four industry high performance cesium Tube 5071A 35[0641|1188|1642|2166].

For the redundant time scale generation and its local distribution we use two identical setups of

- Datum AOG 110
- TimeTech high-performance frequency distribution 10273
- TimeTech pulse distribution 10188.

A third time scale is based on one of the cesium clocks and is distributed within the lab.

The frequency standards are locally measured using

- Two identical setups of sequential time interval measurement systems using
  - a Fluke PM6681,
  - an Agilent 34970A Switching unit,
  - four reference and 16 measurement channels by using three HP34905A RF multiplexers.
- TimeTech six-channel PCO phase comparator.

The time-interval measurement systems are capable of each measuring 20 1-pps differences per minute using a flexible scheduler interfacing the GPIB instrumentation in a GNU/Linux environment. The clock ensemble is measured every 10 minutes. The PCO continuously measures the clock ensemble with a 1-second sampling and is interfaced using IP networking.

Long-haul measurement time transfer instrumentation at SP consists of:

- a TimeTech Satre TWSTFT ground station, 8-W SSPA, 1.8-m dish (see Figures 3 and 4)
- two Javad GGD timing GNSS receivers, SP01, SP02, redundant setup referencing UTC (SP)
- an IGS SPT0, Javad GGD timing GNSS receiver, referencing the SigmaTau maser
- an Oncore UT single frequency receiver for national standard performance time links
- a TW Fiber SDH 10G system referencing UTC (SP) (see Figure 5).

The GNSS receivers are connected to different antenna mounts (see Figure 6). For the SDH time transfer system, the lab has three CISCO 12000 routers at its disposal. As of end of 2009, one router is actively used with an OC192/STM64 connection to the STUPI timing lab, which also provides additional IP connectivity for NTP and real-time data transfer between the other national sites and the IGS. There are a number of NTP servers that use a redundant set of time scale and time code generators on different network segments. Most systems are based on a special 1-pps interfacing hardware. Further, there is a computerized speaking clock system interfacing the national time scale UTC (SP).

Figure 2. Clock room at SP. All clocks, two H-masers, and four 5071A cesium clocks, are placed in this temperature- and humidity-controlled chamber of about 8 m^2. RMS temperature variations were smaller than 0.3 K during 2009. The UTC (SP) time scale is generated by using an H-maser as the master clock and a Datum Auxiliary Output Generator (AOG). Pulse and frequency distribution are placed close to the time scale and the signals are routed as short as possible to different time transfer equipment. The clock room contains also sensible measurement equipment such as a femtosecond phase comparator, the TWSTFT modem, the GNSS receivers, and the SONET/SDH time transfer equipment.

EQUIPMENT AT STUPI

The clock ensemble at STUPI consists of:

- Active hydrogen maser MHM2010 407210
- Active hydrogen maser CH1-75A 407211
- Active hydrogen maser CH1-75A 407212
- two high-performance 5071A 35[0572|1531]
- five standard performance 5071A 36[0223|1175|2068|2218|2297].

STUPI has further a number of CS clocks and a hydrogen maser that are not reported to the BIPM. Most clocks are placed in a temperature/humidity-stabilized clock chamber. The time scale is generated and locally distributed by

- a Datum AOG 110
- HP5087A frequency distribution amplifiers
- an Austron pulse distribution amplifier.

Figure 3/4. TWSTFT outdoor unit with SSPA and LNA. The system uses different polarization for receive and transmit to Telstar 11N@11.4 degrees elevation, which makes the RF section very simple and robust. The SSPA is connected using a flexible waveguide, whereas the LNA is directly coupled to the horn. The Cometech transceiver is located in a room directly below the 1.8-m dish and, thus, protected from the weather and excessive temperature variations. The system also features a satellite simulator that is used to monitor systematic delay changes of the ground station.

Figure 5. The two-way SONET/ SDH time transfer system is a prototype system that consists of a discrete set of instruments. The optical OC192/STM64 connection (at 1550 nm) is power-spitted close to the line card of a CISCO 12000 router and then converted to electrical 10 Gbit/s signals. SDH header recognizers generate an 8 kHz replica of the router clocks of the respective front- and back end of the link, which in turn are compared to UTC (SP) using Pendulum CNT90 time-interval counters. Similar equipment was placed at STUPI in Stockholm at a baseline of about 560 km. The setup has been continuously measuring since summer 2007.

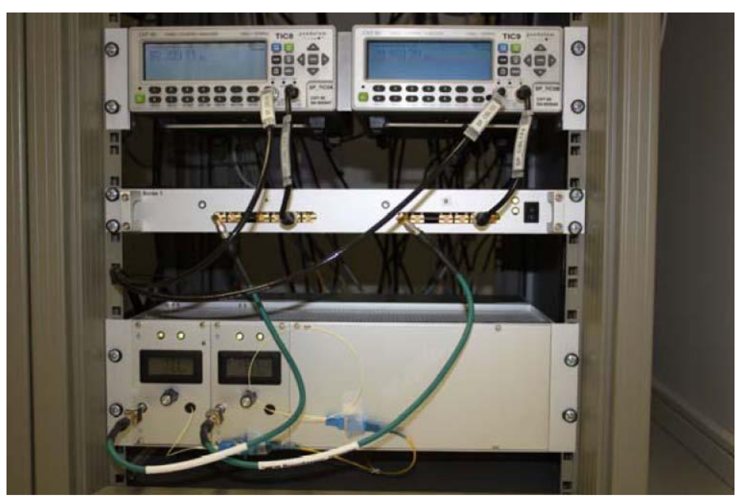

Figure 6. GNSS antennas at SP. The time and frequency laboratory has a number of GNSS antenna systems available. The main antenna is placed on top of the IGS Antenna Monument SPT0 (10425M001) (left picture). The antenna is an AOAD/M_T (258) connected to the power splitter at the lab with about 70 m of phase-stable Andrew FSJ antenna cable. The cable is kept to within a few degrees in temperature-controlled water pipe underground from the lab environment and within and to the top of the concrete pillar. Since late 2009, the OSOD type radome is also temperature-stabilized at 23 ± 3°C using a prototype air heat exchange system that is mainly used for snow melting. This installation has also helped to improve our GPSP3 time transfer that suffered from excessive code multipath in the antenna system during summer months due to unexplained temperature sensitivity of the antenna LNA. Other antennas at SP are roof-top installations (e.g. right picture) that are used together with the National Land Survey of Sweden (LMV), for example for their Network RTK services or for general SP GNSS research.

The local measurement system consists of:

- a Pendulum CNT81
- an Agilent 34970A Switching unit
- four reference and 16 measurement channels by using three HP34905A RF multiplexers.

The sequential time-interval measurement system is capable of measuring 20 1-pps differences per minute using a flexible scheduler interfacing the GPIB instrumentation in a GNU/Linux environment. The setup is very similar to that at SP. The clock ensemble is nominally measured every minute.

The time transfer instrumentation at STUPI consists of:

- two Javad GGD timing GNSS receivers, PL01, PLT0, redundant setup referencing the local time scale
- a PL02, Javad GGD timing GNSS receiver, referencing CH1-75A (407211)
- a TW Fiber SDH 10G system referencing the local time scale.

STUPI has early been committed in IP and network-time research and has a wide range of equipment for IP communication at its disposal. The laboratory maintains a number of public primary NTP servers both for IPv4 and IPv6. Most of the NTP services reference its time to the local realization of UTC, which in turn is traceable to UTC via SP.

Figure 7. Part of the clock chamber at STUPI.

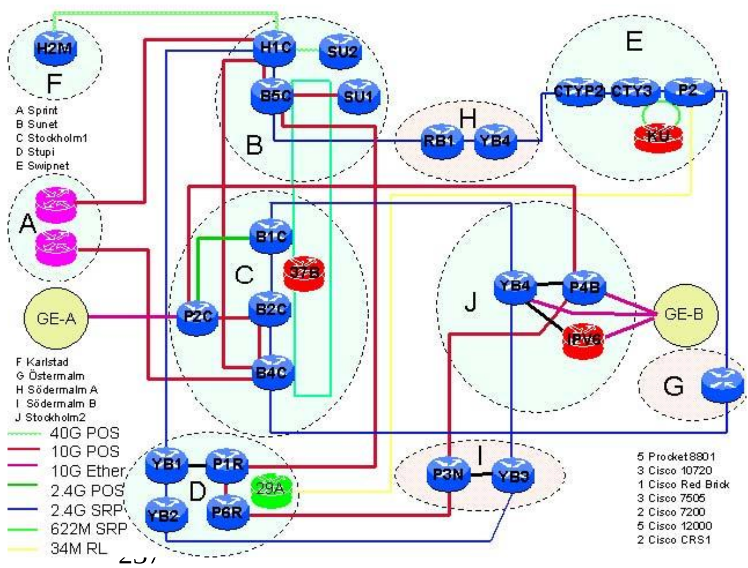

Figure 8. STUPI IP research network in Sweden.

EQUIPMENT AT OSO

The clock ensemble at OSO consists of:

- active hydrogen maser CH1-75A 407218
- active Hydrogen maser CH1-75A 407221
- one standard-performance 5071A 362295

The time scale is generated and locally distributed by

- a Symmetricom AOG 110
- a TimeTech high-performance frequency distribution 10273
- TimeTech pulse distribution 10188.

The local measurement system consists of:

- a Pendulum CNT81
- an Agilent 34970A switching unit
- four reference and eight measurement channels by using two HP34905A RF multiplexers.

Also at OSO, the time-interval measurement system is capable of measuring 20 1-pps differences per minute using a flexible scheduler interfacing the GPIB instrumentation in a GNU/Linux environment. The clock ensemble is measured every 1 minute.

Figure 9. Part of the clock chamber at OSO.

Figure 10. VLBI subsystem is driven by one of the H-masers, primary CH1-(407211), and can be used as a time and frequency transfer link to other VLBI stations with a link performance comparable to that of GNSS carrier phase. In the foreground, the Onsala GPS antenna monument (10402M004) can be seen. It is one of the longest-lived GPS antenna points in the world, with measurements dating back to 1986.

Long haul measurement time transfer instrumentation at OSO consists of:

- two Javad GGD timing GNSS receivers, OS01, OS02, redundant setup referencing the local time scale
- IGS ONSA, Javad GGD timing GNSS receiver, referencing CH1-75A (407211)
- 20-m mm-wave radio telescope for use in astronomy and geodetic VLBI.

GENERATION OF UTC (SP)

The laboratory is equipped with several atomic frequency standards located and maintained in the so-called clock room in the laboratory. UTC (SP) is derived from one selected clock and steered towards UTC using an AOG (see Figure 11). The physical definition of UTC (SP) is at the output connectors of the AOG. The 5-MHz output of the AOG is connected to the input of a frequency distribution amplifier (FDA) and the 1-pps output is connected to a pulse distribution amplifier (PDA), as illustrated in Figure 12.

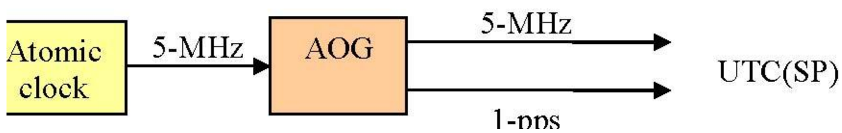

Figure 11. Generation of UTC (SP).

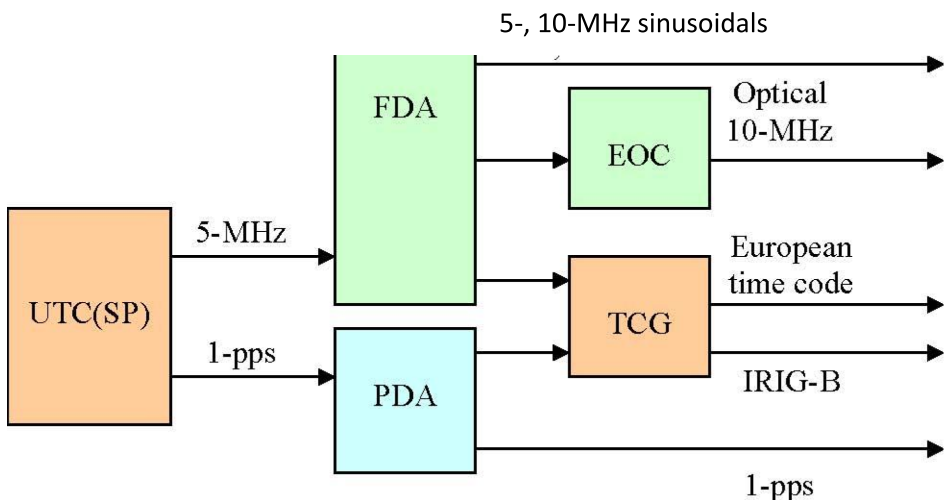

Figure 12. Distribution of UTC (SP) within SP.

UTC (SP) as realized according to Figure 11 is distributed within the time and frequency laboratory, as well as to other laboratories at SP which need time and frequency signals, according to Figure 12. The distribution units (several FDA and PDA) are used to distribute sinusoidal signals and pulsed 1-pps signals to instruments within the laboratory. The optical 10-MHz signals are used for frequency distribution to other laboratories within SP. The European time code is used for the time dissemination equipment (see below) and the IRIG-B code is presently used by time displays located in local conference facilities and meeting rooms.

The laboratory also realizes two backup time scales which are kept as close as possible to UTC (SP) and generated with the purpose of having redundant and independent time scales for the dissemination of UTC (SP).

A more detailed view of the generation of UTC (SP) is illustrated in Figure 13. One of the atomic frequency standards or clocks is chosen as the master clock. This clock, usually a hydrogen maser, is physically connected to the AOG whose output defines UTC (SP). All other clocks are members of an ensemble clock which is calculated in real time and updated as soon as new clock data are available from the time-interval counter. At each update, the ensemble clock gives new prediction estimates of the time and frequency offset of the master clock relative to UTC. These estimates are used as input to the AOG. In addition, each month new data are also available from the BIPM with the difference between UTC and UTC (SP), which also is an input to the ensemble clock algorithm. The ensemble clock algorithm is described in more detail below.

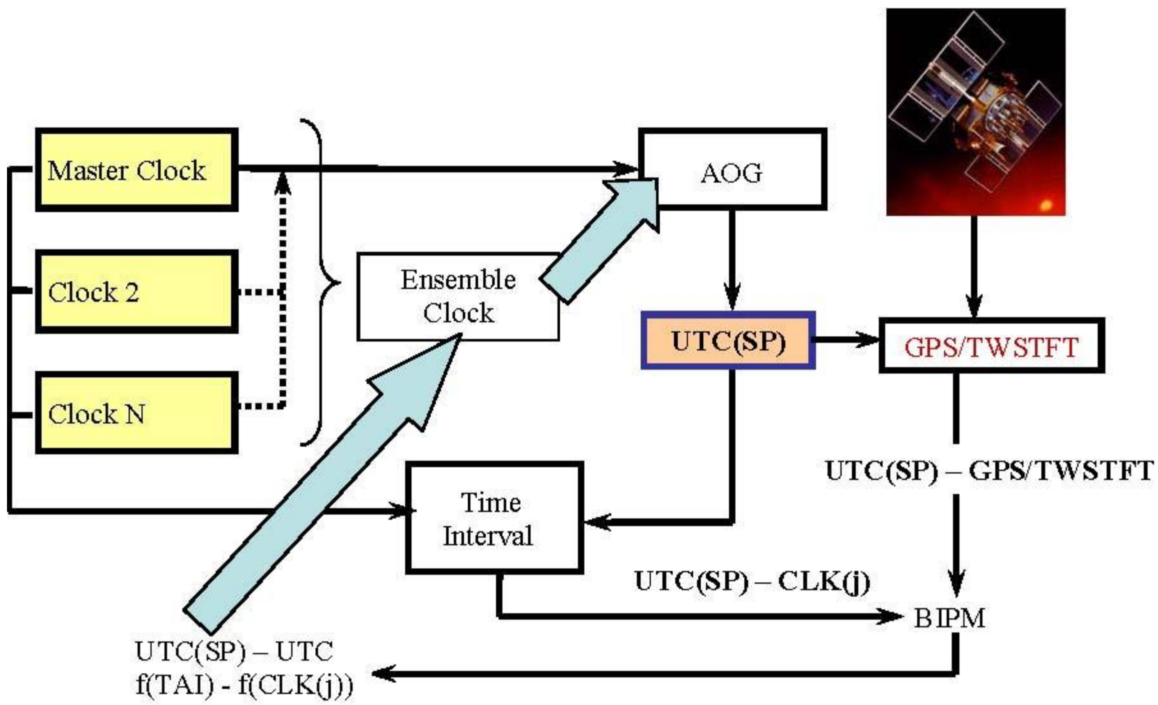

Figure 13. Generation of UTC (SP) through an ensemble clock algorithm and its link to BIPM and UTC through GPS and TWSTFT time links.

TIME LINKS AND TRACEABILITY

SP is the National Laboratory for electrical quantities and time and frequency by appointment of the Swedish government. SP realizes fundamental units such as the volt, ohm, and second from primary standards. Traceability for other units is established from these realizations by means of in-house calibrations and scientific analyses. To ensure international equivalence and acceptance of the established traceability, inter-laboratory comparisons are made between national laboratories. The traceability of UTC (SP) is documented in the BIPM key-comparison data base. According to recommendations from the BIPM, national realizations of UTC should be kept as close as possible to UTC. The goal for UTC (SP) is that it should be kept to UTC ± 100 ns on a long-term basis, without introducing larger frequency steps than ±2 ns/day.

The traceability of UTC (SP) and its relation to UTC is obtained through time links between SP and a reference- or pivot-laboratory selected by the BIPM, presently PTB. The laboratory maintains two active links, one based on GPS and one based on TWSTFT. Both links are evaluated by the BIPM, with one official link (usually TWSTFT) and one as a backup. The accuracy of both the GPS and TWSTFT links has been evaluated **[3-4]**. The local equipment setup of both links is briefly described below.

GPS TIME LINK

The laboratory is equipped with several GPS receivers and three antenna installations. All receivers important for the maintenance of UTC (SP) are connected to a GPS antenna mounted inside a plastic radome on the top of a three-meter-high temperature-stabilized concrete pillar (see Figure 6), via a 70-meter-long temperature-stabilized coaxial cable and a power splitter. The cable is laid inside the pillar and below ground in a pipe which is temperature-stabilized using water of nearly constant temperature. The antenna is fed from a 12-VDC power supply via the power splitter. Since the different receivers may require different signal power levels and, in addition, output a DC-voltage from the antenna-connector, the power splitter is equipped with DC-blocks and if necessary selected attenuators. Figure 14 shows a general sketch of the GPS setup.

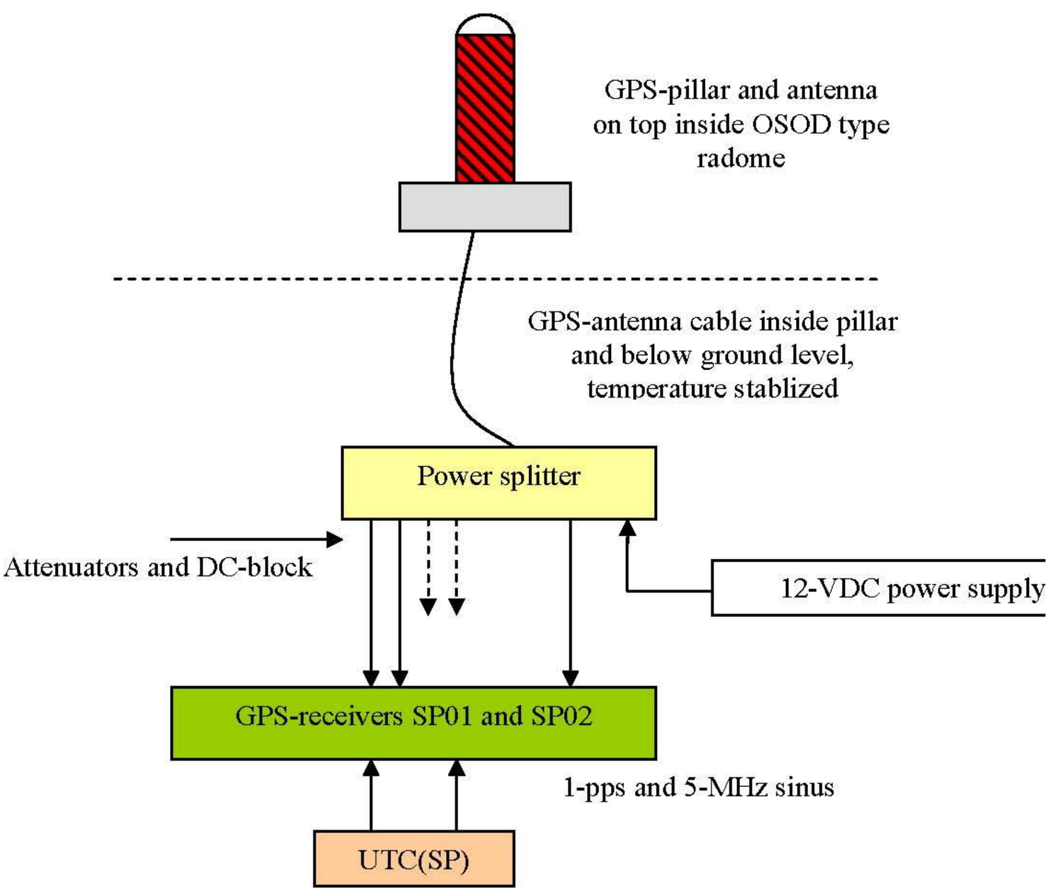

Figure 14. GPS setup.

Two of the receivers are used for the link of UTC (SP) to UTC, whereas one of them is the official laboratory time transfer receiver which GPS data are reported to the BIPM, and the other is a backup, also reported to the BIPM. Both are located in the clock room. The data reported to the BIPM are in the standardized format, as required by the BIPM, and calculated using the so called GPSP3-method utilizing multi-channel, dual-frequency code GPS data **[5]**. Also, RINEX-files containing both code- and carrier-phase data are submitted to the BIPM.

TWSTFT TIME LINK

The laboratory is equipped with a TWSTFT-system for time and frequency transfer over commercial geostationary satellites including modem, transceiver, Earth station, and satellite simulator (see Figures 3 and 4). The outside equipment is located on the roof of the building containing the laboratory or in a room just below the roof. The inside equipment is located in the clock room. Figure 15 shows a general sketch of the TWSTFT setup. The TWSTFT data reported to the BIPM are in the standardized ITU-format, as required by the BIPM **[6]**, and submitted on a daily basis to the BIPM ftp server. The measurements with the TWSTFT system follow a schedule arranged by the CCTF working group on TWSTFT.

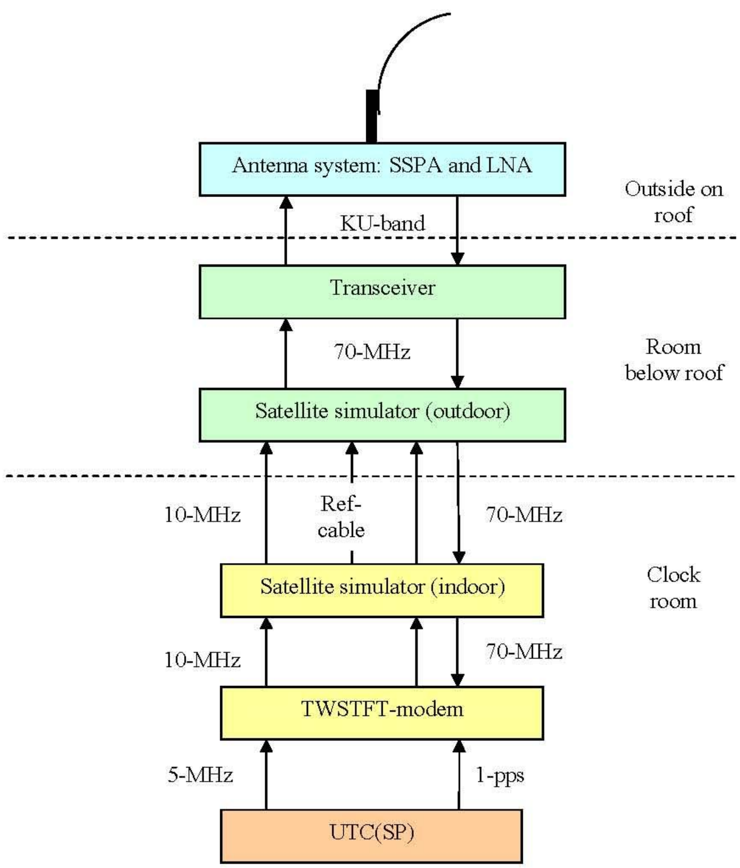

Figure 15. TWSTFT setup.

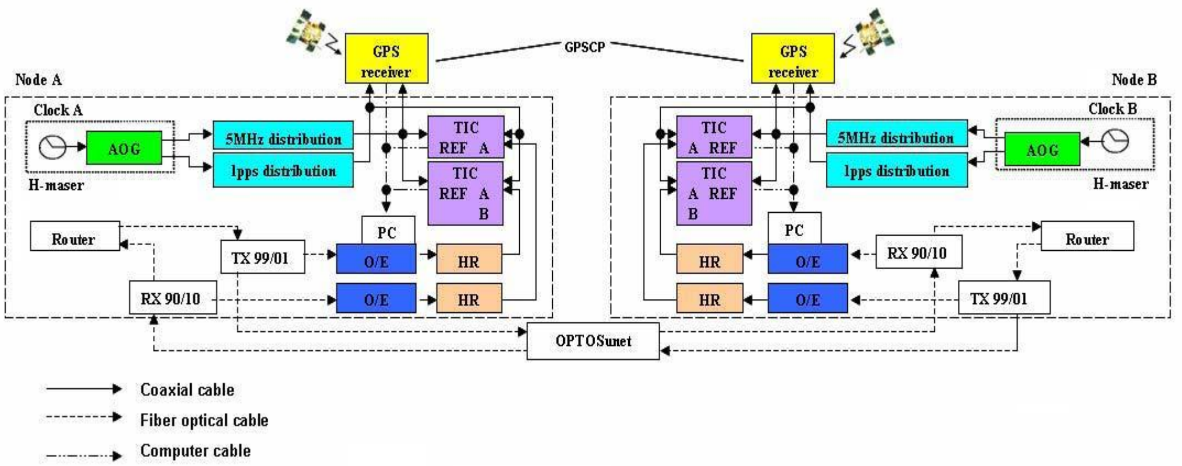

Figure 16. TW fiber time transfer between UTC (SP) (node A) and the time scale at STUPI (node B). 10% respectively 1% of the receiving/transmitted optical power is used to detect the respective OC192/SDH headers generating pulse sequences that are compared to the respective time scales. Presuming that up- and down-link fibers traverse the same environment and have roughly the same length, a two-way differential technique is used to estimate the time differences between the two time scales. GPS carrier-phase time transfer is used to evaluate the fiber time link. RMS differences are generally below 1 ns where residuals correlate well with temperature changes along the track of the fiber pair.

TW FIBER TIME LINK

The SP lab has a unique time link to the STUPI lab, linking UTC (SP) to the realization of UTC at STUPI. It is based on the two-way time difference of the propagation of OC192/STM64 SONET/SDH frames between two routers in SP and STUPI. The system is a prototype and currently used to study its long-term link behavior **[7]**. Figure 5 shows the front-end of the system at SP, whereas Figure 16 shows the schematic of the setup of the complete link.

DISTRIBUTED TIME SCALE

Our vision of a distributed time scale was born from the understanding that today most of a nation's vital infrastructure depends on the distribution of accurate time and frequency. This is especially true for typical synchronous communication networks that will fail as soon as synchronization between its components fails. The Swedish government has invested in the strengthening of critical infrastructure in Sweden due to the importance of time in society. In the case of a disastrous event, society at large should be guaranteed continued basic service. The most principal prerequisite for a robust national time distribution is to build a redundant national time scale. It is up to the legislative to enforce the use of robust time and frequency in all critical systems and reduce the undependable use of GPS as a time source.

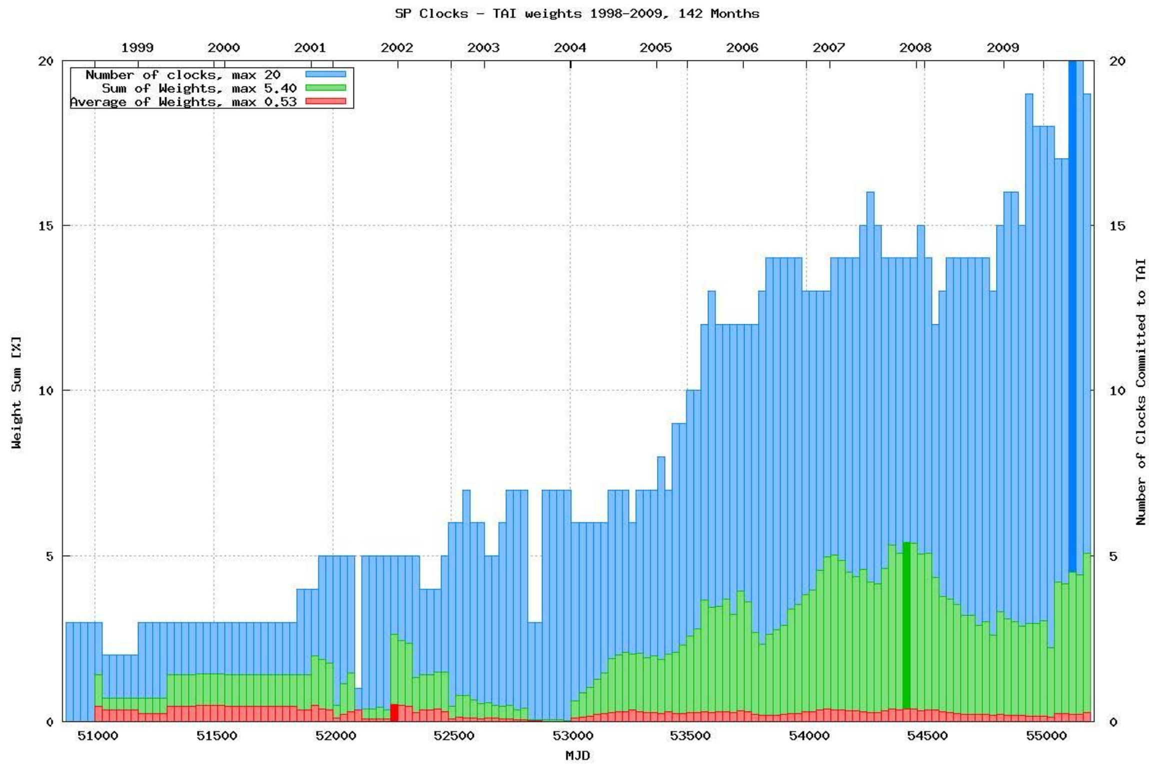

Figure 17. Sweden's contribution to TAI. SP, STUPI, and OSO have contributed up to 20 clocks per month to TAI, which has resulted in a maximum of about 5% of the overall clock weight.

All three time labs at SP, STUPI, and OSO base their respective time scales on a similar setup of master-clock and output generator; see Figure 11. The sister sites are linked to UTC (SP) and to UTC/TAI with help of redundant GPSP3 and PPP links **[8]**. These links were calibrated using clock transports in 2004 **[9]** and 2009 **[10]** respectively[1]. Each of the redundant sites could, thus, in theory act as the official link to the BIPM. Figure 1 shows the logical connection between the laboratories. The introduction of redundant TW fiber-based time links will in future reduce our dependence on GPS. As of end of 2009, each laboratory combines the measurement of its local clocks with the help of ensemble clock software in order to estimate the master clock's offset, frequency, and possibly its frequency drift relative to UTC. This clock model is continuously used to steer the local time scale, while preserving the master clock's inherent stability. At present the local UTC/TAI representations rely on the combined midterm stability of the local group only. As soon as the BIPM publishes Circular-T, the nodes individually calculate the offsets of their and in turn calculate the historic offsets of the local clocks to UTC. These values are fed back to the ensemble clock algorithm that recalculates the time series for the past month and estimates new models. That usually results in differences to the current real-time estimated model, most noticeable by a phase offset. The steering algorithm takes the new model into account and steers the time scale towards the best estimate of UTC using a set of constraints. The ensemble clock filter is based on

[1] STUPI in October 2004 by transporting an H-maser and a Cs clock from SP to STUPI with an estimated uncertainty of 10 ns, OSO in February 2009 by a GPSCP-aided round trip transport of a CS clock with sub-ns uncertainty.

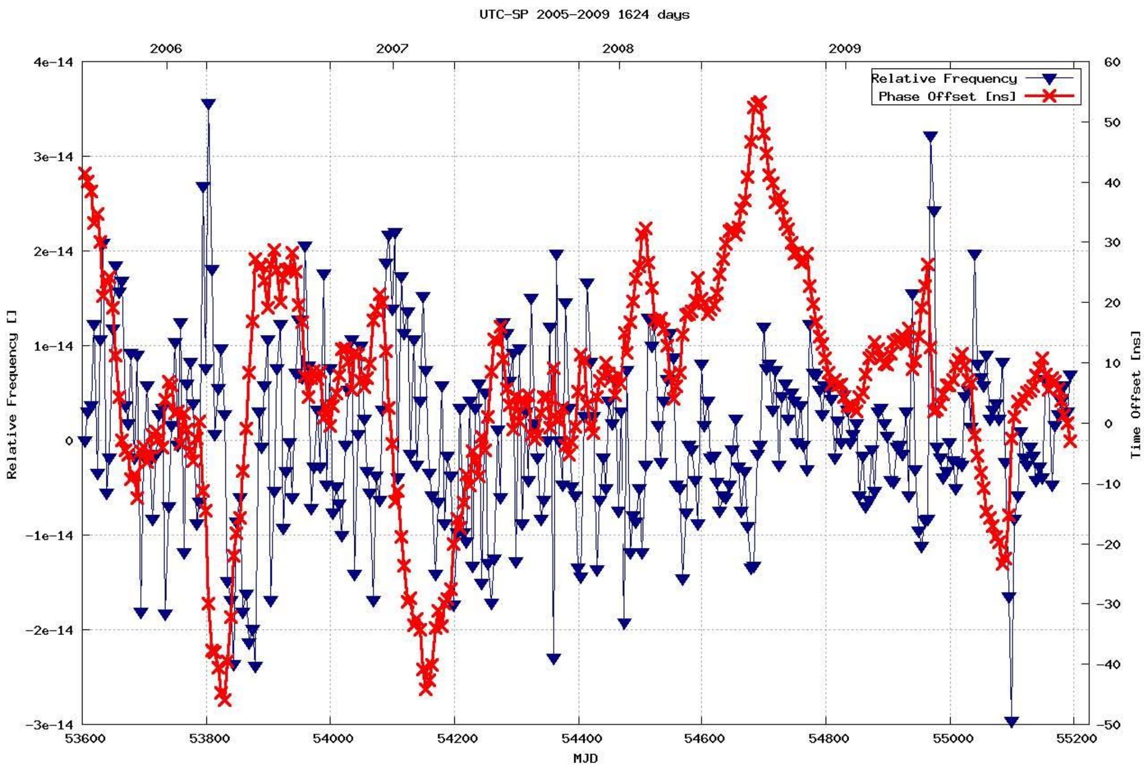

Figure 18. The phase and frequency offset of UTC (SP) during the last 4.5 years. The time series has a 5-day time stability of about 2 ns and a mean frequency of about 5×10^{-16}. Prior to 2005, the policy for the time scale allowed phase offsets exceeding 100 ns. The frequency deviation of the timescale from UTC shall never exceeded 1×10^{-13} and has steadily been within 5×10^{-14} during the last 7 years.

Kalman filtering. The principle of that sort of filtering is a correct definition of all the noise processes describing clock model variations and measurements as well as their correlation to each other. Clock parameter variations are modeled by chained integration of white noise processes, whereas measurements are modeled with white noise. The clock models also inherently define a time-dependent weighting function where clocks with larger accumulated uncertainties in their model parameters have smaller weights. H-masers lose weight in a group composed of both H-masers and Cs clocks with increasing time after the publication of new UTC updates due to the additional uncertainty in the parameter value for the frequency drift. Input to the filter are phase differences between unforced clocks measured with the local measurement systems or external real-time time links. The filter is also capable of handling latent measurements by applying a parallel filter technology, which is also used to update the filter with UTC measurements.

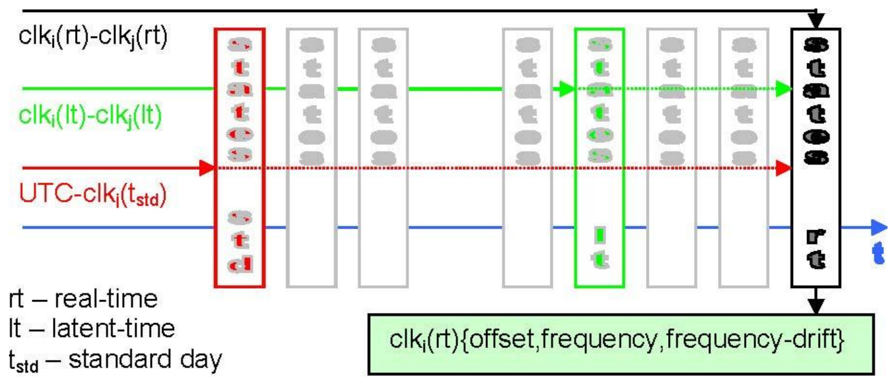

Figure 19. Kalman-based parallel filtering. The real-time states are updated by UTC- and possibly latent clock measurements using all accumulated state information. This method allows easy combination of any post-processed time links with real-time clock differences for the UTC prediction.

DISSEMINATION OF UTC (SP)

SP has concentrated on dissemination of UTC (SP) using NTP. Besides the NTP servers at SP, we have also established three traceable NTP nodes **[11]** at the Swedish national exchange points for Internet traffic **[12]**. Those nodes are securely placed within mined spaces below the ground and are considered critical infrastructure. The system's timing is sustained by a local group of rubidium clocks linked to UTC (SP) using multichannel common view. NTP in a FreeBSD environment are interfaced using 1PPS

Figure 20. NTP installation.

hardware **[13]**. The two redundant NTP servers are network-wise close to the Internet service providers that route their traffic through the node. This guarantees close connections to end users. Both OSO and especially STUPI provide several NTP services referencing their respective timescales to the public domain.

From SP there is still a modem service available that serves UTC (SP) as European time code with latency estimation. Further, a popular speaking clock service is distributed by TeliaSonera **[14]**, where SP provides traceable synchronization and speech synthesis. Customers requiring precision synchronization can be served using GPS Common View/all-in-view techniques based on Motorola Oncore designs or custom setups using geodetic GNSS receivers. The same principles are deployed has for the links to STUPI and OSO. Instrument calibration of time interval and frequency are offered according to **[15]**.

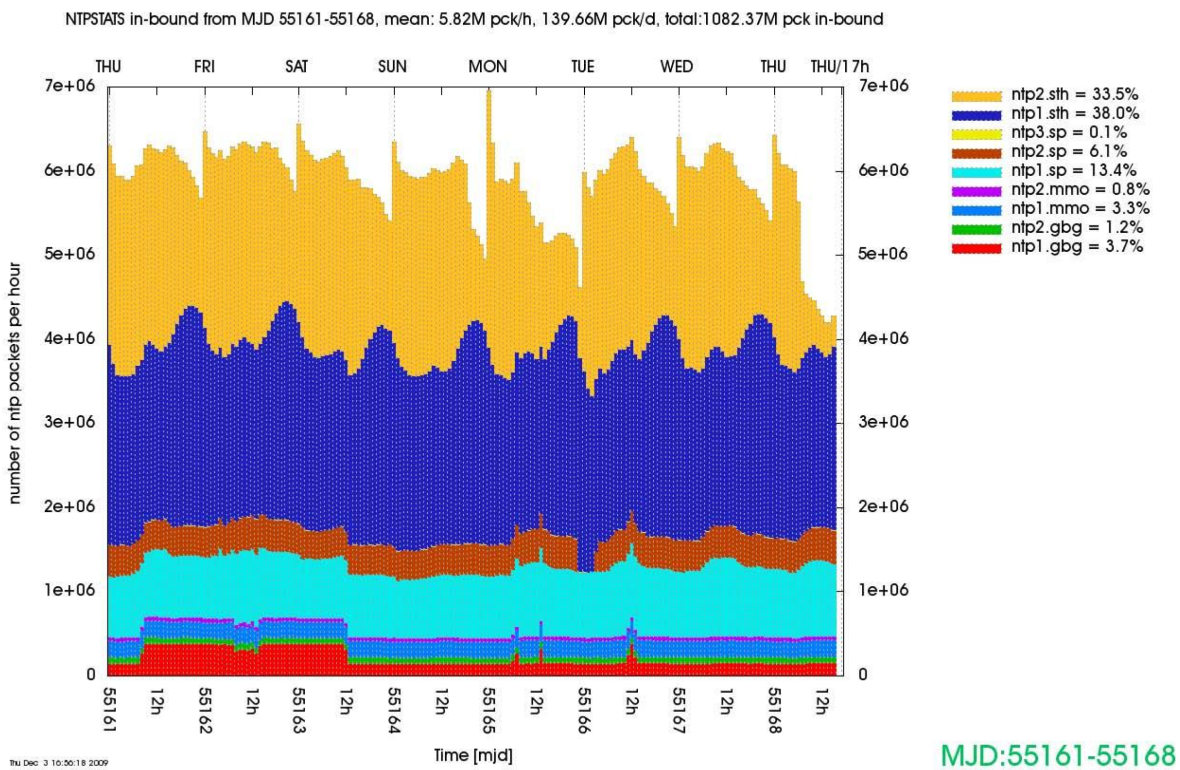

Figure 20. Accumulated NTP traffic in number of (inbound) packets per hour for all the NTP servers that SP is responsible for. The node in Stockholm (sth) is traditionally the one most accessed and usually has about 70% of all traffic. SP's own servers have a steady share of about 20%. The two other nodes are placed in Gothenburg (gbg) and Malmö (mmo). It is interesting to note the anti-correlated behavior of the diurnal in the amount if traffic between the two servers in Stockholm. The Netnod servers are also served by the ntp.se pool.

RESEARCH AND DEVELOPMENT

The time and frequency section provides competence and technical expertise to industrial and governmental customers and partners. We often lead development and research projects within the areas of time metrology, geodetic positioning, and atmospheric research. Further, the group is involved in studies of advanced mathematical methods and generally tries to have a lateral view on neighboring research areas. Ongoing projects 2009/2010 include:

- GNSS carrier-phase time transfer, development of a SP real-time software to be used for the distributed national timescale **[16]**
- Time scale algorithm based on Kalman filtering **[17]**, deployment in the distributed national timescale
- Development of a minimized version of the TW fiber transfer system based on synchronous and asynchronous communication networks for deployment in critical Swedish infrastructure **[7]**
- One-way optical time and frequency transfer methods **[18]**
- Climate evaluation studies **[19]**
- Studies of ionospheric influence on network real-time kinematic services **[20]**
- VLBI time transfer
- Network time, primary NTP, development of new methods **[21]**.

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Some commercial products are identified in the text for the purpose of clarity. All trademarks used are properties of their respective owners.

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