Principles of Two Way Time & Frequency Transfer

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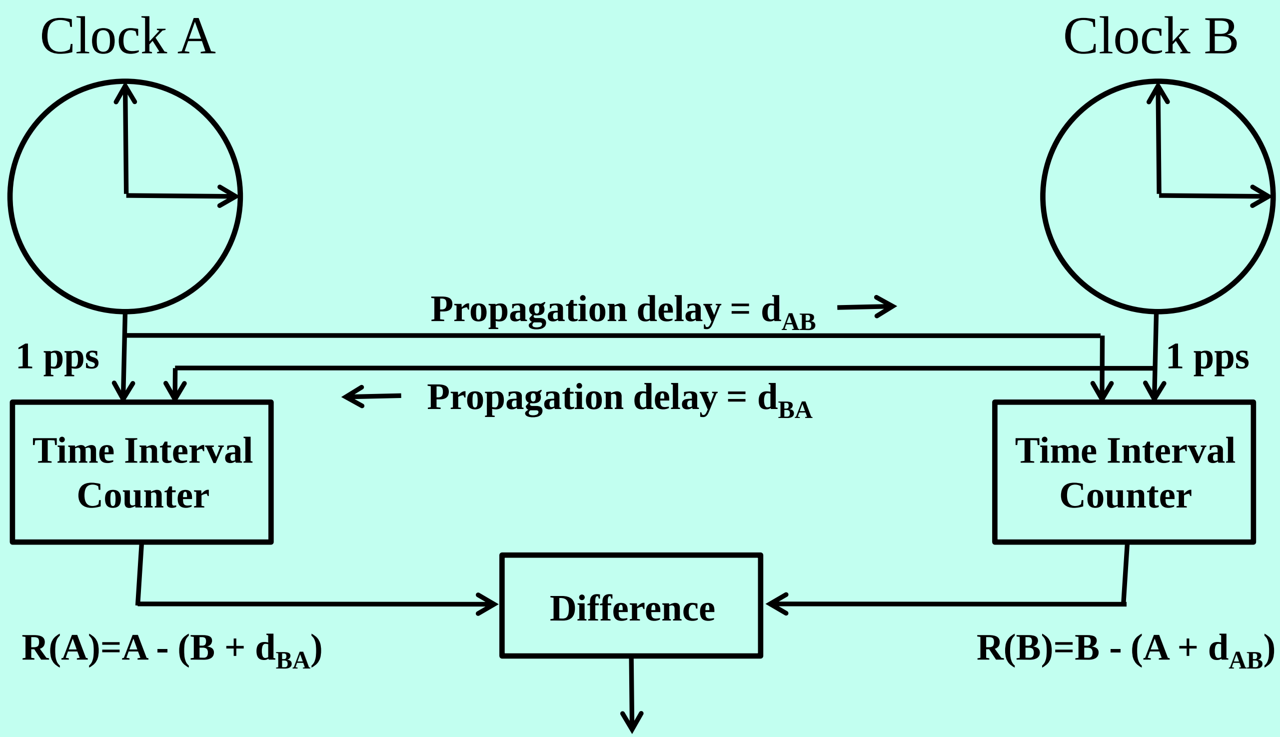
Basic Principles of a Two Way Technique

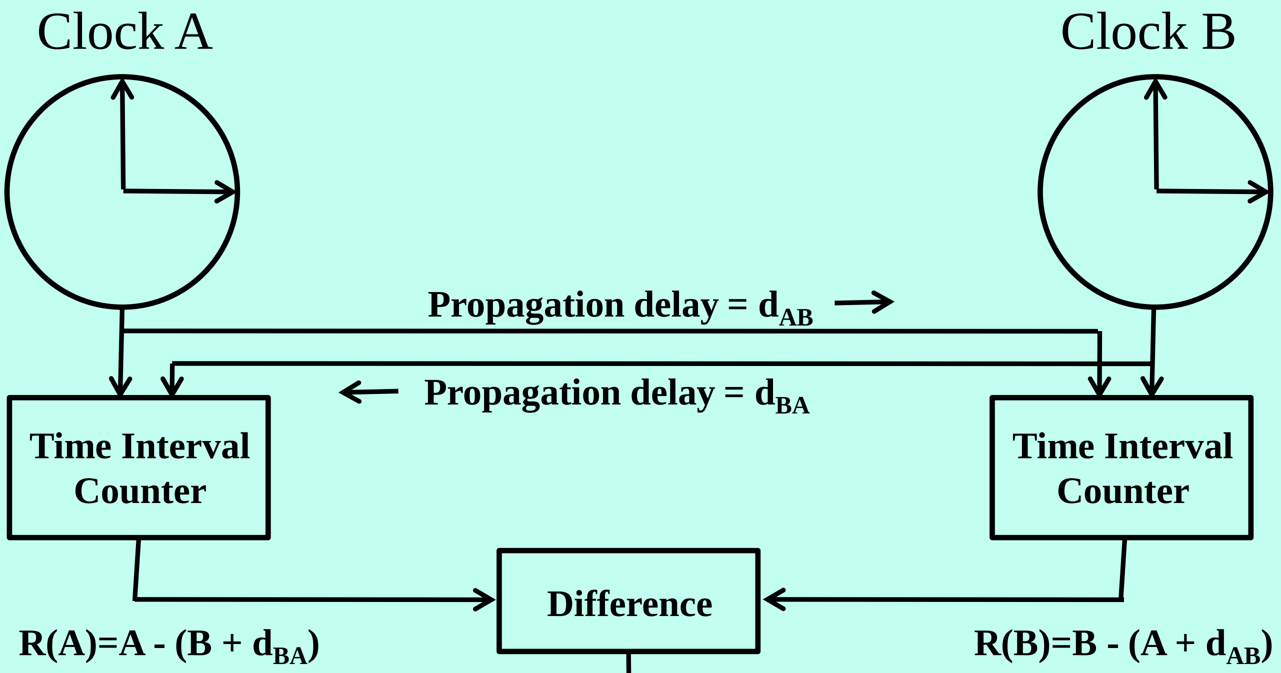


$$\frac{R(A) - R(B)}{2} = (A - B) + \frac{(d_{AB} - d_{BA})}{2}$$

If we assume that propagation delays are reciprocal, i. e., $d_{AB} = d_{BA}$ then we get

$$(A - B) = \frac{R(A) - R(B)}{2}$$

Basic Principles of a Two Way Technique

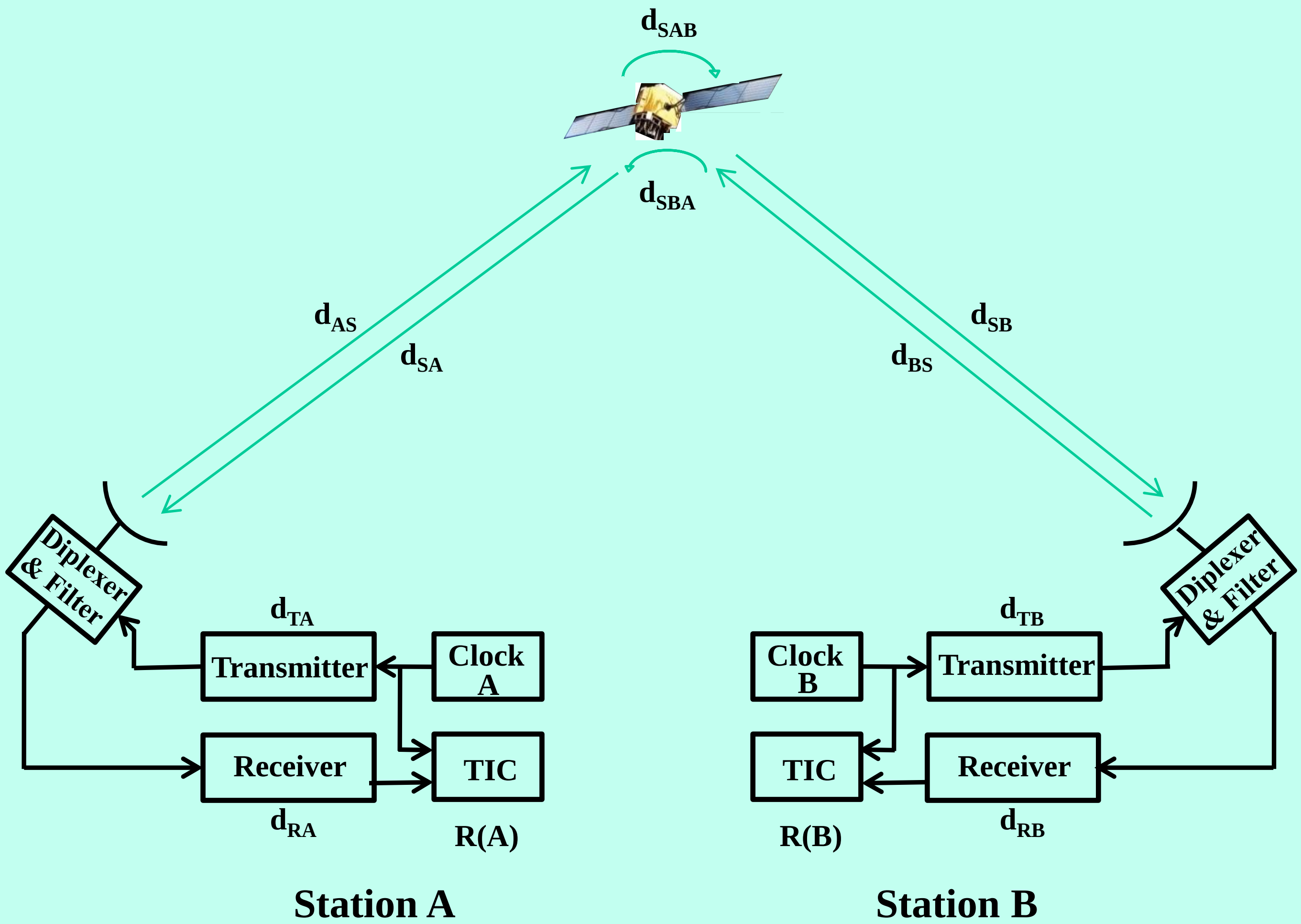


$$(A - B) = \frac{R(A) - R(B)}{2}$$

The Main Advantage of the Technique is that the Propagation Delay cancels out provided the propagation paths are reciprocal.

The key requirement of the technique is Simultaneous Transmission and Reception and Time interval measurements at both ends.

Two Way Time Transfer using a Satellite



$$R(A) = A - (B + d_{TB} + d_{BS} + d_{SBA} + d_{SA} + d_{RA} - 2\omega A/c^2)$$

$$R(B) = B - (A + d_{TA} + d_{AS} + d_{SAB} + d_{SB} + d_{RB} + 2\omega A/c^2)$$

Two Way Time Transfer using a Satellite

The difference of TIC Readings between two Stations

$$\begin{aligned} R(A) - R(B) = 2(A - B) &- (d_{TB} - d_{RB}) + (d_{TA} - d_{RA}) \\ &+ (d_{AS} - d_{SA}) - (d_{BS} - d_{SB}) + (d_{SAB} - d_{SBA}) \\ &- 4\omega A/c^2) \end{aligned}$$

Rearranging and Simplifying we get the Clock Difference

$A - B = \frac{1}{2}\,.[R(A) - R(B)]$	← **Difference of TIC readings**
$- \frac{1}{2}\,.(d_{TA} - d_{RA}) + \frac{1}{2}\,.(d_{TB} - d_{RB})$	← **Earth Stn. Equipment**
$- \frac{1}{2}\,.(d_{AS} - d_{SA}) + \frac{1}{2}\,.(d_{BS} - d_{SB})$	← **Propagation effects**
$- \frac{1}{2}\,.(d_{SAB} - d_{SBA})$	← **Satellite Transponder**
$+ 2\omega A/c^2)$	← **Earth Rotation (Sagnac effect)**

Typical Implementation Details

- Space Segment

Geostationary Communication Satellites
INTELSAT/EUTELSAT/INTERSPUTNIK
Leased Commercial Transponders

- Communication Band

C-Band :- 6GHz uplink / 4GHz downlink
Ku-Band :- 14GHz uplink / 11GHz downlink
Bandwidths of a few MHz

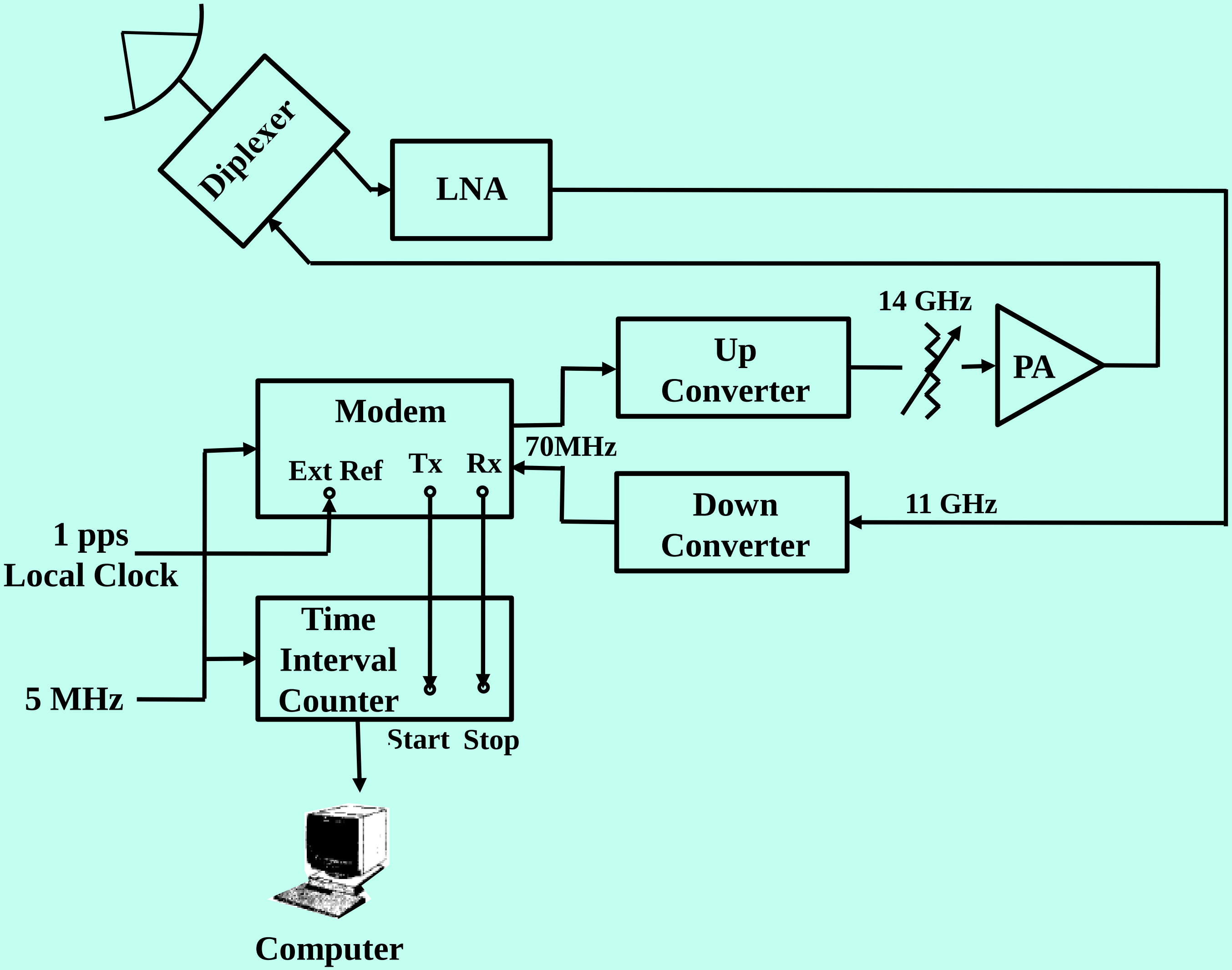
- Earth Station Equipment

VSAT Terminals with 1.8 m Dish Antenna, state-of-the-art LNA's and SSPA's of few watts and providing an IF of 70 MHz

- Signal Modulation

Binary Phase Shift Keying (BPSK) modulation with Pseudo Random Noise (PRN) sequence. Typical Chip frequency of 1-10 MHz

Typical Earth station Equipment



Discussion of Individual Delay Components

- **Propagation Delay between Earth – Satellite – Earth**

The signal Path is mainly free space with small amount of ionosphere and troposphere.

The path followed by uplink and downlink are essentially the same path.

The free space part is completely reciprocal.

The tropospheric part is also reciprocal since at Ku band signal delay is frequency independent.

Only the ionospheric part is slightly non reciprocal, since the signal delay through the ionosphere has a $1/f^2$ dependence. Considering the uplink and downlink at 14GHz and 11GHz and the Ionospheric Total Electron Content (TEC) of $10^{18}/m^2$, the non reciprocity component **works out to be less than 100ps**.

Discussion of Individual Delay Components

- **Satellite Transponder Delay**

The satellite transponder equipment has a small delay variation across the transponder bandwidth.

The non reciprocity of the delays between d_{SAB} and d_{SBA} can arise if we use two different frequency channels for sending the signal along A to B and B to A. This would happen if we use FDMA mode.

Generally nowadays the Modems use almost identical frequencies for all stations and distinguish them by using different PRN codes. This is the CDMA mode. In such a case, the delays in either direction are identical and **the difference is zero**.

Discussion of Individual Delay Components

- **Earth Station Equipment Delay**

The delay of the signal through the earth station equipment involves waveguides, Cables, amplifiers, frequency converters, filters and also the PRN Modem.

Different delays are encountered in the transmit & receive chains at the two stations, which gives rise to significant non reciprocity due to this source.

It is difficult (or almost impossible) to determine the individual delays through the various components.

Usually a transportable earth station is used to calibrate the total Equipment related delay. This terminal is collocated with each of the earth stations, one at a time, for a Two way measurements using a common clock source.

Discussion of Individual Delay Components

•Delay caused by Sagnac Effect

This effect is due to the rotation of the Earth. Clocks on the earth are not in an inertial frame of reference. Hence the exchange of timing information is subject to a relativistic correction.

As shown in the Figure in the next slide, the signal path is effectively lengthened in case the timing pulse is travelling from west to east. Conversely, the path is effectively shortened for a signal going from east to west. The exact change in path length is $2\omega A/c^{2}$, where ω is the Earth's angular velocity and A is the projection of The satellite ray paths onto the equatorial plane.

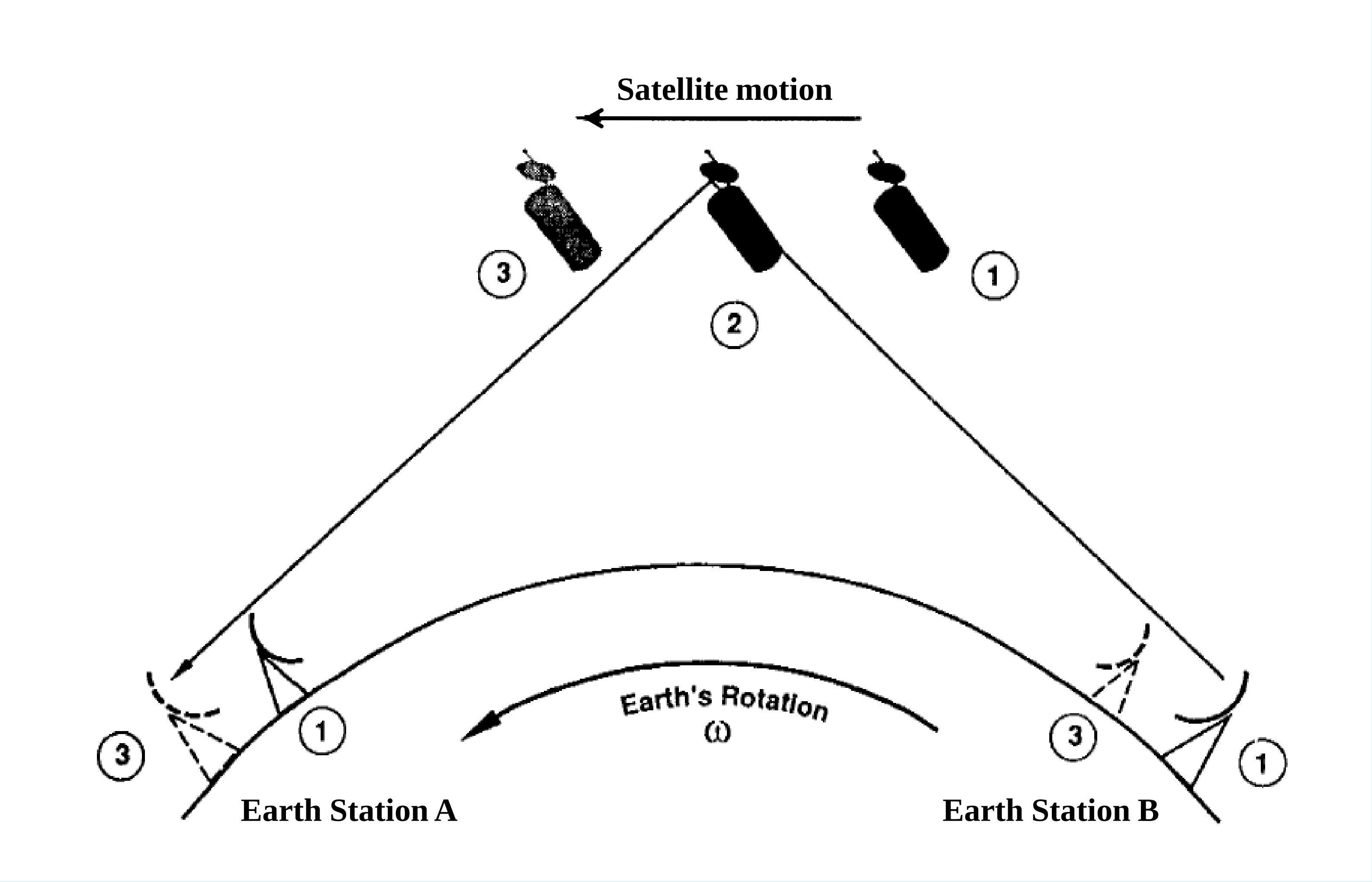
In order to calculate this source of delay with less than 100 ps error, we need to know the station locations to better than about 300m.

The error of Sagnac delay **can be ~ 100ps** for an error of 1° in satellite longitude.

There can be a **variation of ~50ps** in the Sagnac delay due to finite eccentricity of the satellite

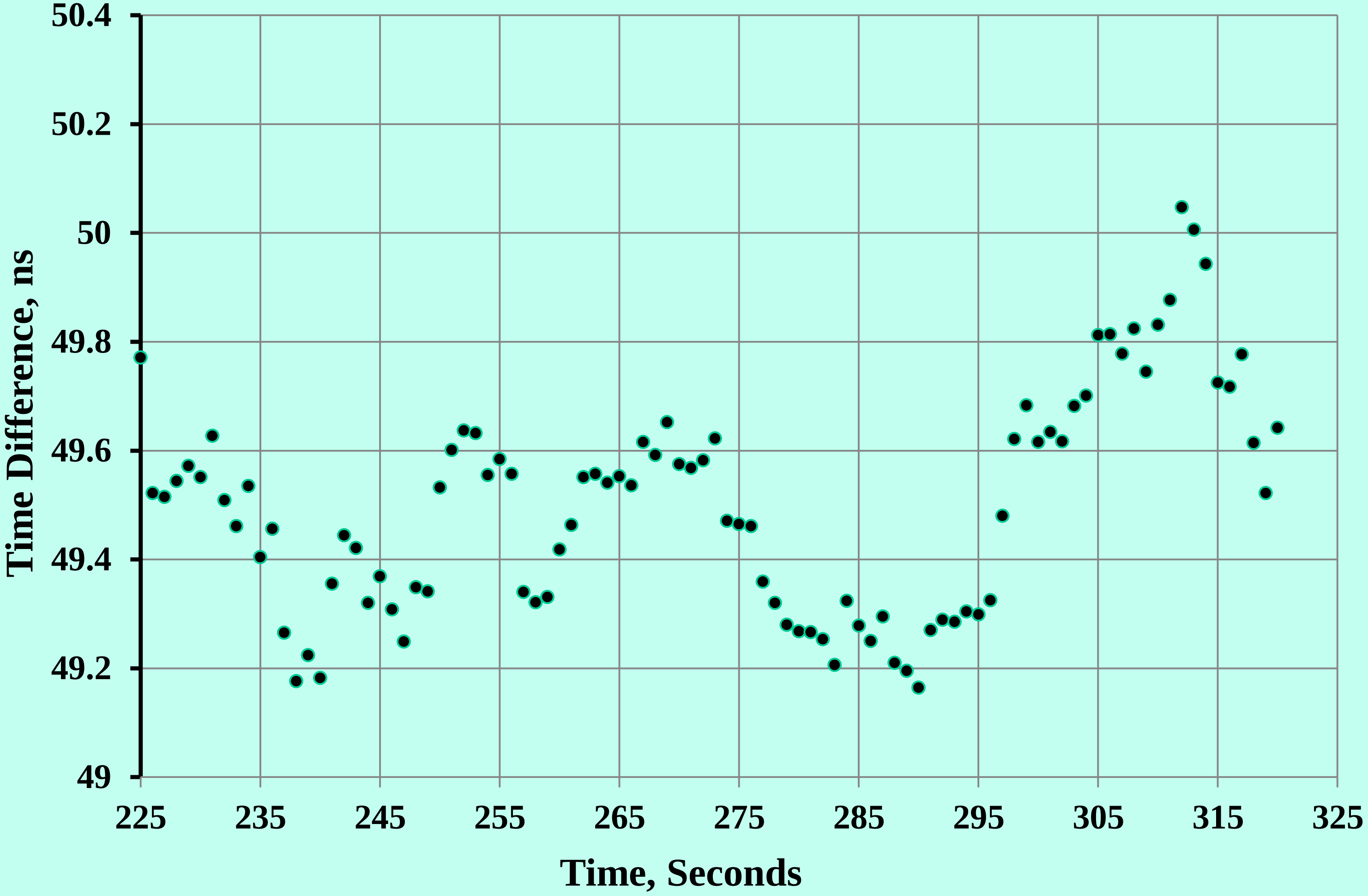
Discussion of Individual Delay Components

- **Pictorial Illustration of Sagnac Effect**



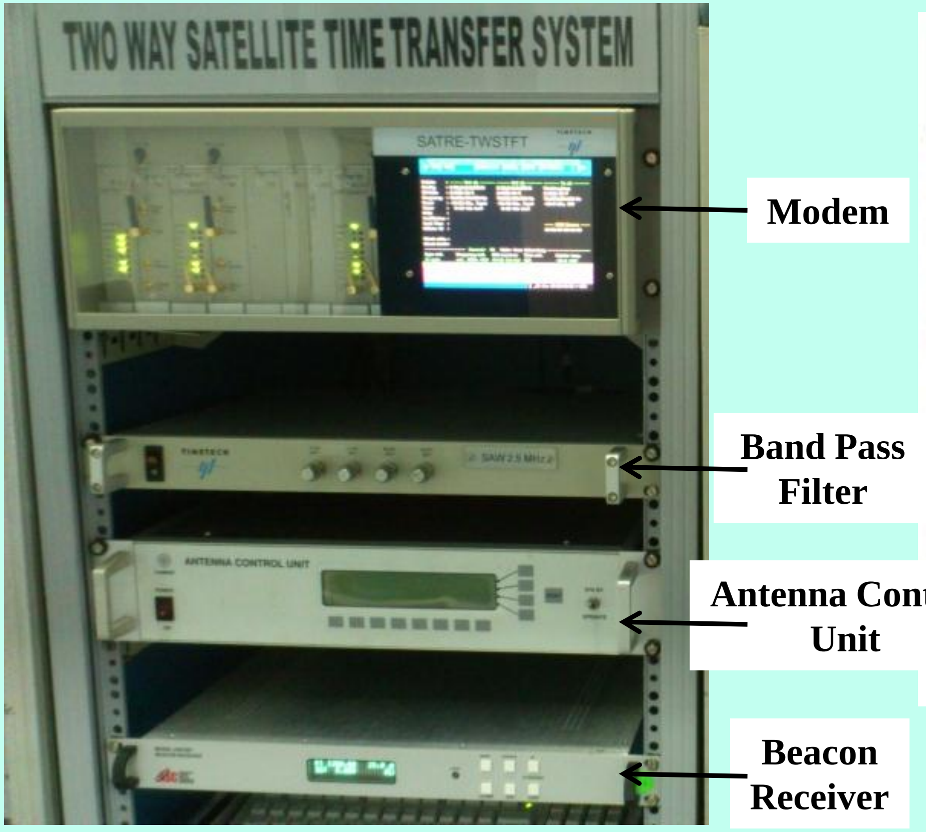
This view is as seen from the Earth's North Pole

Typical Recorded data illustrating Jitter



Time scale difference between UTC(NPLI) &UTC(PTB)
Data points shown for 100s illustrating a jitter of ~ 200 ps

Photographs of Typical Two Way setup



Summary

Two Way Time Transfer used with geostationary communication satellites is a practical technique for comparison or synchronization of clocks at the level of better than a nano second.

Advantages

- We can use leased transponder on any satellite rather than dedicated satellites
- Satellite location is required only to be able to point antennas rather than compute delays.
- Effects of ionosphere and troposphere are negligible without need for modeling.
- Location of the clocks on the ground need to be known only within few hundred m
- Equipment delays can be calibrated using a portable earth station.
- Simple averages of few hundred 1 sec measurements can yield precisions of ~300ps

Disadvantages

- Participants need to simultaneously transmit and receive.
- The total Equipment setup is very expensive.
- There is a recurring cost of leasing the transponder time, which has to be shared among the participants.

Thank You for your Attention !