ACCURATE DELAY CALIBRATION FOR TWO–WAY TIME TRANSFER EARTH STATIONS

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INTRODUCTION

The most accurate clocks are using cesium beam frequency standards as their source of accuracy. The atomic time scale TAI is built from the SI seconds after adopting the definition of its origin. As a practical time scale close to the astronomic time, UTC has been introduced, which is equal to TAI, but kept in close agreement with universal time by addition or subtraction of leap seconds. UTC and TAI are computed by the BIPM from the time comparison data of laboratory and commercial cesium clocks. The accuracy of comparing clocks all over the world has been improved significantly by the use of the GPS common view method. This one way method is capable of precision around 8 ns and accuracies of about 30 ns if not deteriorated by Selective Availability measures.

A further improvement can be realized by using two–way methods, as demonstrated in several experiments using groundstations at each clock site capable of reception and transmission. This paper addresses the calibration of the groundstations to achieve high accuracy in such two way time comparisons.

GENERAL PRINCIPLES OF TIME COMPARISON

To measure the difference of the time scales of two clocks a time interval counter is used. One clock output is connected to the start of the counter, and the other clock output (1 pps) to the stop input. State of the art counters measure the difference with a resolution of 20 ps, and an accuracy of 100 ps or 0.1 ns.

If the clocks are not adjacent to each other, a cable can be used to transport the output signal of the second clock to the stop input of the time interval counter. However, the time interval reading is not correct because of the propagation delay of the 1 pps signal in the cable. This delay is to be measured and corrected for. A 50 Ω coaxial cable has typically a delay of about 5 ns/m.

If the cable is relative long then distortion of the pulse occurs which gives an extra delay. In a cable the higher frequency components are attenuated more than the lower frequency components, and the cable acts as a low pass filter. To avoid such a group velocity distortion, modulation of the 1 pps signal on a carrier frequency can be done. In this manner the additional delay from distortion can be minimized.

Instead of using a cable for transportation of such a modulated carrier the space can be used by means of transmitters and receivers with the appropriate antennas. This is done with low frequency

transmitters for time signals such as WWVB at 60 kHz in the U.S. and in Europe: DCF77 at 77.5 kHz, MSF60 at 60 kHz, HBG at 75 kHz; also in Loran–C and HF standard frequency and time transmitters. The maximum reception distance is several thousands of kilometers.

A problem for accuracy is the determination of the distance from transmitter to receiver and to correct for propagation properties of the medium: troposphere, ionosphere, (barometric pressure, humidity, degree of ionization).

Recently satellites are being used. One problem here is the very long distance and the accuracy of the determination of this distance. Another problem is the ionospheric delay; the latter however is inversely dependent by the square of carrier frequency and amounts less than 1 ns at 12 GHz.

The two–way method using satellites eliminates the need to determine separately the exact distance from each station to the satellite, as is shown in the next section.

TWO–WAY TIME COMPARISON

From Figure 1 we can see that the difference of the clocks at station 1 and 2 can be determined. In this figure:

TA(k) is the time scale at station k;
TI(k) is the time interval reading;
TT(k) is the transmitter delay;
TR(k) is the receiver delay;
TU(k) is the uplink delay;
TD(k) is the downlink delay;
TS(k) is the satellite delay;
TC(k) is the correction for relativistic effects.

The difference TA(1) - TA(2) is to be determined. The reading at station 1 is:

$$TI(1) = TA(1) - TA(2) + TT(2) + TU(2) + TS(2) + TD(1) + TR(1) + TC(1)$$

The reading at station 2 is:

$$TI(2) = TA(2) - TA(1) + TT(1) + TU(1) + TS(1) + TD(1) + TR(2) + TC(2)$$

The difference gives:

$$
\begin{aligned}
TI(1) - TI(2) = 2\{TA(1) \quad &- \quad TA(2)) + TT(2) - TT(1) + TU(2) \\
&- \quad TU(1) + TS(2) - TS(1) + TD(1) \\
&- \quad TD(2) + TR(1) - TR(2) + TC(1) - TC(2)\}
\end{aligned}
$$

or:

$$
\begin{aligned}
TA(1) - TA(2) = \frac{1}{2}\{TI(1) \quad &- \quad TI(2) + TT(1) - TT(2) + TU(1) \\
&- \quad TU(2) + TS(1) - TS(2) + TD(2) \\
&- \quad TD(1) + TR(2) - TR(1) + TC(2) - TR(1)\}
\end{aligned}
$$

If the same transponder in the satellite is used, then:

$$TS(1) = TS(2)$$

If the satellite is not moving too fast then:

$$TU(1) = TD(1) \text{ and } TU(2) = TD(2),$$

and their delays cancel.

The TC(1) and TC(2) can be calculated accurately enough.

The remaining terms are now:

$$TA(1) - TA(2) = \frac{1}{2}\{(TI(1) - TI(2) + TT(1) - TT(2) + TR(2) - TR(1) + C\}$$

If the transmit delays TT and the receive delays TR at both stations were equal then they would cancel. But that can only be proved by measuring the difference by locating two groundstations close enough together, which is not a simple action. Even then the sum of the transmit difference and the receive difference is determined, not their values separately.

Therefore here a method to determine the absolute value of the transmit– and receive–delays separately is described.

THE TIME TRANSFER MODEM

The MITREX modem (Figure 2) has a modulator section in which the 1 pps signal is impressed on a bi–phase modulated carrier. The PRN generator is clocked at a 2.5 MHz rate and every 4 ms a bit sequence is generated. As soon as the 1 pps signal appears, then one sequence of 4 ms is inverted. The sequence is reclocked simultaneously with the 1 pps transmit output pulse and it then modulates the phase of a 70 MHz carrier frequency. The signal is band pass filtered and is fed as the IF signal to the upconverter and transmitted.

The demodulator section receives the 70 MHz downconverted signal and provides a 1 pps received pulse as soon as it detects the 4 ms inverted PRN sequence.

The sum of the internal delays in the modem can be measured by connecting the 70 MHz output with the 70 MHz input and connecting the 1 pps transmitted output to the start input of a time interval counter and the 1 pps received output to the stop input. The delay of any external cable can be measured by connecting the cable also between modem output and input. The cable delay is found by subtracting the internal modem delay.

THE CALIBRATION OF THE GROUND STATION DELAYS

A typical earth station is shown in Figure 3. The delay between the reference plane at the time interval counter and the plane at the antenna is to be determined. First the delay between the antenna and the modem reference plane will be measured. For this purpose a passive satellite transponder simulator is constructed. It is consisting of two double balanced mixers connected in series between two SMA to wave guide transitions acting as antennas. The mixers convert the transmit frequency (14 GHz) to the receive frequency (11 GHz). So one local oscillator is tuned to 2.93 GHz and the other is at 70 MHz.

The modem is used to measure the sum (TT + TR) of the transmit delay TT and the receive delay TR through the satellite simulator at the modem reference plane.

This is similar to the test loop translator which in some groundstations is installed between the output of the upconverter and the downconverter input, but now the delay in the antenna feeds is also included.

In order to determine the values of the transmit and receive delay separately, the 70 MHz cable to the satellite simulator is used. The delay of this cable CS is measured first. Therefore it is disconnected from the simulator and so are the 70 MHz cables CT and CD to the up– and the downconverter respectively.

First cable CT is interconnected to cable CD at the far end and the sum delay (CT + CD) is measured.

Then cable CS is substituted for CT and the sum delay (CS + CD) is measured.

Finally (CS + CT) is measured. From the obtained 3 measurements the delay of cable CS is calculated:

$$CS = \frac{1}{2}\{(CS + CD) + (CS + CT) - (CT + CD)\}.$$

Also the other cable delays are calculated in this way.

The calibrated cable CS is reconnected to the satellite simulator and the other cables are also reconnected. The next step is to connect cable CT to the 70 MHz continuous carrier and cable CS to the modulated 70 MHz modem output. Now the CW carrier of 14 GHz is PRN modulated in the satellite simulator. The sum of CS and the receive delay TR from simulator to modem input is measured: (CS + TR).

The delay CS is known, so TR can be calculated. The sum (TT + TR) of transmit delay TT and TR was already measured, so TT can also be calculated.

DETERMINATION OF THE INTERNAL DELAYS IN THE MITREX MODEM

It should be emphasized that in the preceding paragraph TT and TR are measured to the reference plane at the modem 70 MHz in– and output. Still undetermined is the internal transmit delay Tt with respect to the 1 pps received output.

Let us look again at the modem in Figure 2. The transmit part is the simpler, after the reclocking a wide–band mixer is used (delay estimated <2 ns) followed by a band–pass filter. Filters exhibit always delays, inversely proportional to their bandwidth. Also the receiver has a band–pass filter at its input. So the transmit filter was taken out of the circuit and then the total internal delay was measured again. The difference in delay between filter in and out the circuit gives the delay of the filter.

The other internal transmit delays are calculated from the measured internal cable lengths from the wideband mixer to the 70 MHz output connector of the modem. Once the total internal transmit delay Tt being determined, the internal receive delay Tr is calculated by subtracting the transmit delay Tt from the total internal delay.

FINAL CALIBRATIONS

Now the internal delays Tt and Tr can be added to the external groundstation delays to find the total receive delay as well as the total transmit delay from the antenna reference plane to the time interval

counter reference plane.

The systematic uncertainty, appearing from estimation of the internal delays of the mixer in the modulator and in the satellite simulator, is estimated to be less than 2 ns. The statistical uncertainty, or precision, is of the order of 1 ns but is depending upon the averaging time.

At VSL, the antenna is connected to the modem with IF coaxial cables of about 120 m. The values found were: TT = 669.2 ns, TR = 648.6 ns, CS = 628.7 ns, Tt = 319.3 ns and Tr = 845.3 ns. So an asymmetry of 505.4 ns exists.
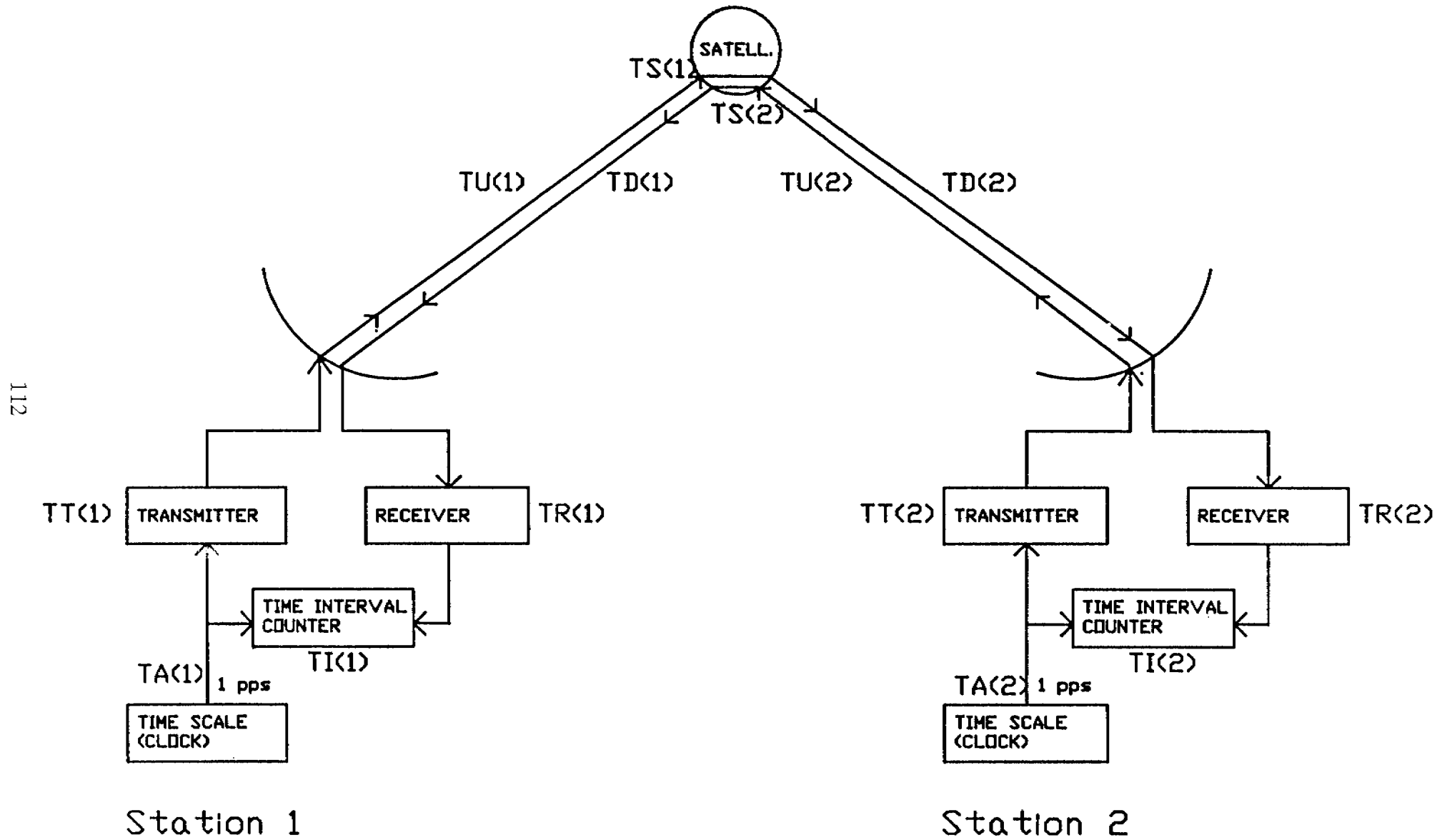
CONCLUSION

In this paper it has been shown that with the described calibration method using a satellite simulator all transmit and receive delays can be determined to the nanosecond level accuracy. It is important to measure accurately the transmit and receive delays at each two–way earth station; symmetry should not be assumed at the nanosecond accuracy level.

The internal delays between input and output antennas of the satellite and the difference in position of the satellite antennas relative to each earth stations should be treated similarly.
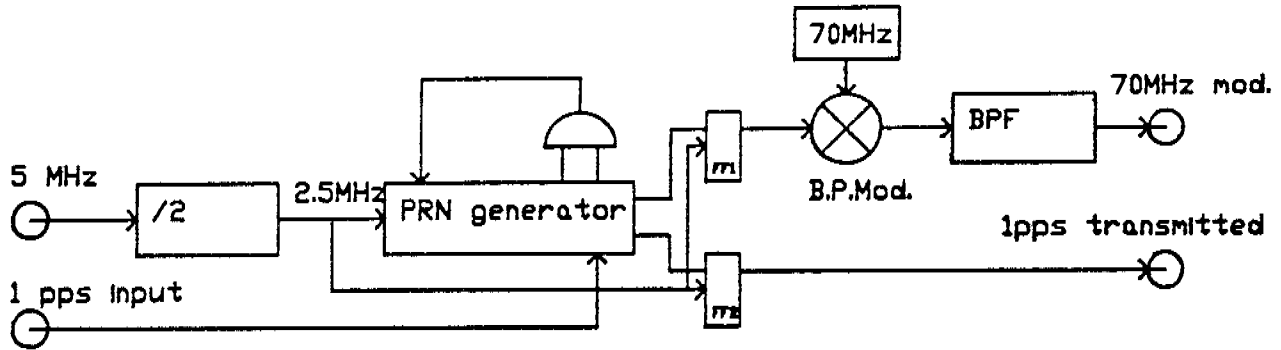
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Fig. 1 Two-way Time Comparison Principle

Mitrex Modulator section

5 MHz

1 pps input

/2

2.5MHz

PRN generator

m

70MHz

B.P.Mod.

BPF

70MHz mod.

1pps transmitted

Mitrex Demodulator section (receiver)

Correlators

70MHz input

BPF

Late

Early

PRN generator

+

−
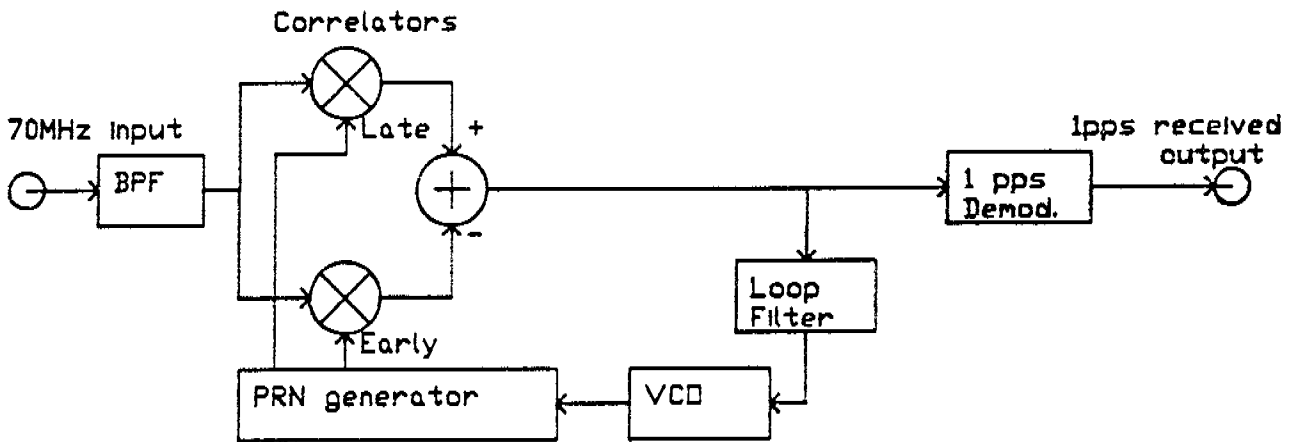
VCO

Loop Filter

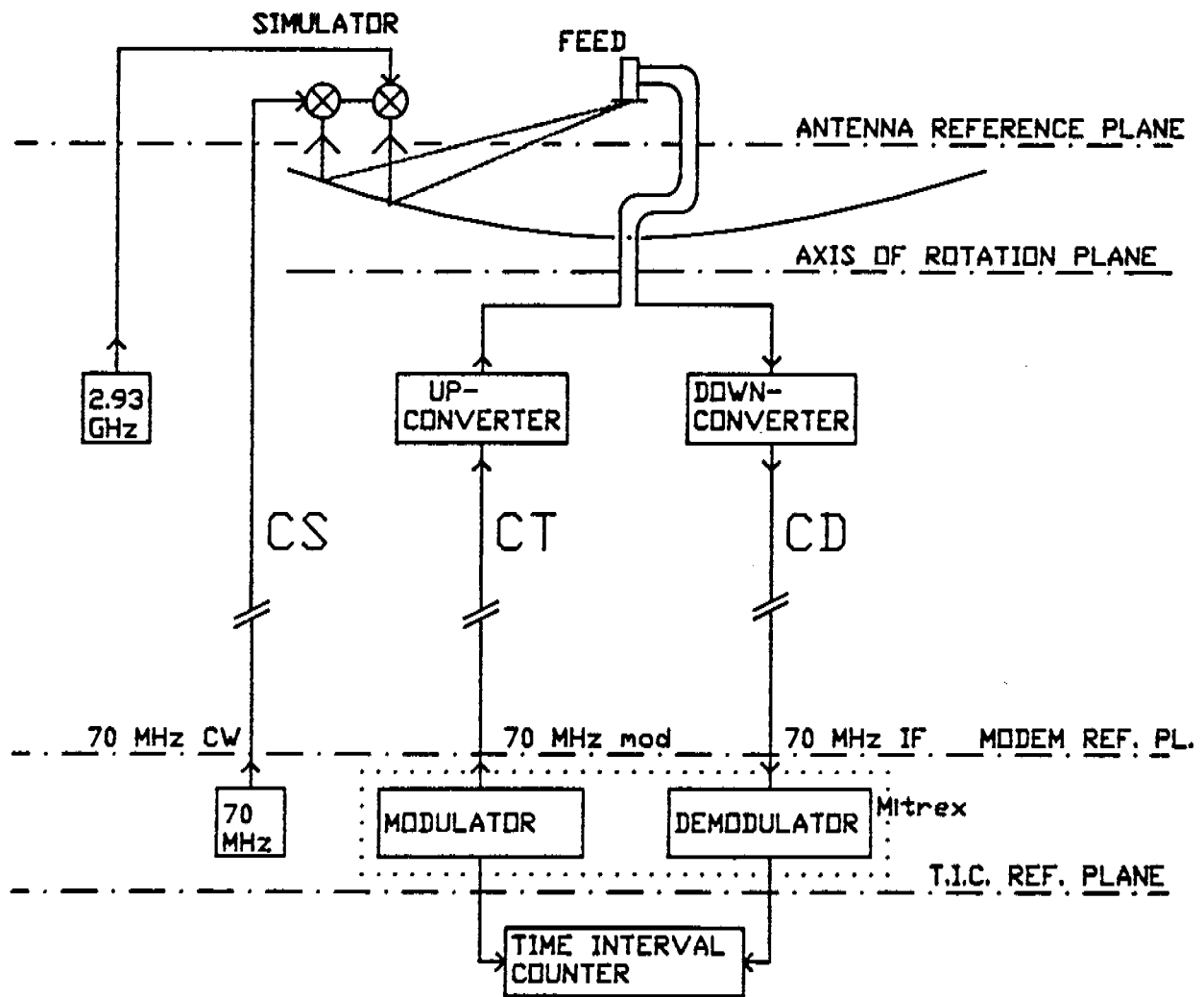1 pps Demod.

1pps received output

Fig. 2 Mitrex Modem

Fig. 3 Earth Station Calibration

QUESTIONS AND ANSWERS

DAVID ALLAN, NIST: Do you have a way of checking the one nanosecond accuracy number, or is that an internal calculation?

MR. DE JONG: It is the sum of the uncertainties of the readings of the time interval counter and the uncertainty in the measurement of the lengths of the coaxial cables and of the two mixers of the simulator. The mixers have not been measured, but we could take out, for example, the 70 MHz mixer and see what the difference would be in the total delay. It would be a lot of work and it is of the right order of magnitude for the total uncertainty.