EVALUATION AND IMPROVEMENTS OF THE CALIBRATION OF A TWSTFT STATION USING SATSIM

Gerrit de Jong and Roland van Bemmelen
NMi Van Swinden Laboratorium
P.O. Box 654
2600 AR Delft
The Netherlands

Abstract

As part of the Galileo project of Early Trials on Time Synchronization Techniques and Calibration Issues, the TWSTFT automated station delay calibration system using a special Satellite Simulator developed by VSL (SATSIM) at NMi-VSL was evaluated. This was done to verify the obtainable uncertainty level with this technique. The results of the evaluation will be presented. The stability of the station delay calibration has been reported earlier. The problem of reflection in cables used for GPS, Glonass, and TWSTFT has been reported earlier and may cause systematic errors and temperature sensitivity. The SATSIM system has now been checked for these reflections by revealing them by a new method with varying frequencies. Some imperfections were found and corrected; the final uncertainty results are now at the nanosecond level.

1 INTRODUCTION

1.1 GENERAL

The work described in this paper was done in the framework of the Galileo project as part of an ESA Early Trials study on Time Synchronization Techniques and Calibration Issues. Part of it was also calibration issues (experimentally), which are not treated with the required care today, but that are important to meet the required level of accuracy for the Galileo system (i.e. nanosecond level) and for timing users. Addressed in this paper is the validation of the calibration of transmit and receive delay difference of a TWSTFT system at NMi-VSL using a Satellite Simulator Method (SATSIM) calibration system.

1.2 ACCURACY AND UNCERTAINTY EXPRESSION

The result of the validation is the expression of the uncertainty of results from the SATSIM system at NMi-VSL. The ISO *Guide to the Expression of Uncertainty in Measurement* (GUM) **[1]** and the EAL document EAL-R2 **[2]** discern two types of uncertainties related to measurements: the uncertainty evaluated from the statistical analysis of the data (denoted Type A) is u_A and the uncertainty evaluated from other causes denoted Type B is u_B. So Type B evaluation includes estimates of contributions from systematic nature and Type A evaluation includes contributions from random nature. Type A in the field

of Time and Frequency is mostly expressed as ADEV, MDEV, and TDEV. The total combined uncertainty u_C is calculated as the root of the sum of the quadratics of u_A and u_B. To obtain a confidence level of 95%, a coverage factor k = 2 is generally used. In the form of a formula: $u_C = 2 \cdot \sqrt{(u_A^2 + u_B^2)}$. The term accuracy should be avoided for measurement results.

1.3 CLOCKS AND TIME SCALE AT VSL

NMi-VSL uses a high-performance cesium clock (HP5071A) followed by a phase microstepper for UTC (VSL), which serves as the direct reference for the GPS receiver and as indirect reference for the TWSTFT. The TWSTFT equipment is directly connected to a second high-performance cesium clock followed by a phase microstepper and in the data the difference with UTC (VSL) is incorporated.

2 CALIBRATION OF A TWSTFT SYSTEM

2.1 DESCRIPTION OF THE TWSTFT SYSTEM COMPONENTS

The setup of a TWSTFT is described in **[3]** and **[4]**. It consists of a modem that modulates the 1PPS Ref (= 1PPS TX) from the local clock on an IF carrier of 70 MHz (Figure 1). An up-converter transforms this 70 MHz TX to the transmit frequency Fup, which in this experiment was the 14.0 to 14.5 GHz up-link band for INTELSAT. A solid-state power amplifier (1 to 4 W) sends this to the transmit feed of the antenna with a diameter of about 2 m. The signal is transmitted to the satellite and received by the remote site. The signal from the remote site is sent to the satellite and received as Fdn by the receive feed of the antenna. A low-noise amplifier amplifies the weak signal (56 dBHz) and a down-converter brings the signal Fdn down from 12.5 GHz to an IF of 70 MHz. The modem demodulates this IF signal and recovers the remote 1PPS as 1PPS RX.

The clock difference can be calculated only if at each station the difference between the propagation delay of the 1PPS TX to the antenna feed and the propagation time of the 1PPS RX from antenna feed to 1PPS TX out is known. Also any change in this TX-RX delay affects the calculated clock difference. Delay changes in any component have this result. So it is an advantage to use a method that measures as directly as possible the wanted quantity TX-RX delay. The SATSIM method does this task, with the exception of the TX-RX delay of the modem. The manufacturer of the modem provides the latter.

2.2 PRINCIPLE OF CALIBRATION WITH SATSIM

The principle of the TWSTFT station transmit and receive delay calibration using a special satellite simulator (SATSIM) is described earlier (see **[5]** and **[6]**). The delay measurement system **[4]** for an earth station for Two-Way Satellite Time and Frequency Transfer is repeated here shortly.

The SATSIM (Figure 2) is placed in front of the antenna. Its task is to down-convert the transmit signal Fup (i.e. 14 GHz) to the receive signal Fdn (i.e. 12.5 GHz). For this purpose it needs a local oscillator signal of the difference frequency DF (i.e. 14.0 – 12.5= 1.5 GHz). This DF is built up from the IF frequency (i.e. 70 MHz) and the local oscillator signal of (DF-IF) GHz, i.e. 1.430 GHz.

The SATSIM, thus, has four ports: TX-in (Fup), RX-out (Fdn), IF-in (70 MHz), and (DF-IF)-in (DF-70MHz). The TX-in and RX-out ports are coupled to a small antenna with dual linear polarization, for INTELSAT the TX and RX polarities are orthogonal. The ports are symmetrical and, thus,

interchangeable. The DF-IF port receives the required (DF-IF) frequency of sufficient amplitude for the mixer in the SATSIM.

The IF port receives a continuous wave (CW) carrier at the IF frequency when the sum of the TX delay and the RX delay of the equipment is to be measured (Figure 3a). It receives the modulated TX signal at the IF frequency from the modem when the sum of a calibration cable designated CAL (= Cable C including Amplifier + cable L) plus the RX delay of the station is to be measured (Figure 3b).

In the case that the delay of the CAL cable is known, then, after measuring the sum CAL+RX, the value of the RX delay is calculated by subtraction of the CAL value. From the sum TX + RX the value of RX is then subtracted to find TX. Then the searched value TX-RX can be calculated.

The delay value of cable C can be determined together with two other cables A and B by measuring the three delays while interconnecting, at the far end, subsequently cable A with cable B (Figure 3.c), cable C with cable A (Figure 3d) and cable C with cable B (Figure 3e). The delay of C is then calculated using the three-cornered-hat method: cable C = ½{Delay(cable C + cable A) + Delay(cable C + cable B)-Delay(cable A + cable B)}.

Then cable L is measured by inserting it in series with cable C, repeating the measurement for the delay (C+B+L), and subtracting the earlier measured (C+B). The delay CAL is the sum of the cable C and cable L delays. These measurements can also be automated as has been done at NMi-VSL.

2.3 AN AUTOMATED SATSIM CALIBRATION SYSTEM

The SATSIM calibration system has been automated by using coaxial switches that are controlled by software to realize the interconnections needed for the calibration (Figure 4). It is described in the literature **[4]**.

Also, some detailed results about the long-term stability measurement of the NMi-VSL TWSTFT equipment using this SATSIM system have been shown; see *"Delay stability of the TWSTFT earth station at VSL"* in **[7]** and **[8]**.

2.4 VALIDATION RESULTS OF THE EXISTING VSL SATSIM SYSTEM

In the recent years a problem in systems using PN bi-phase modulation has been revealed. This has to do with reflections (multi-path) in cables transporting bi-phase modulated signals to the receivers containing the early/late correlation detectors. GPS, Glonass, TWSTFT, and also Galileo signals can be affected;.see **[9,10]**.

The SATSIM calibration could also suffer from this phenomenon; the validation of this has been done in this study. One method to do this is to change cable lengths in small portions and check if delays are changing exactly according to the change of electrical length. This is however not a practical method for existing systems.

Another method is to vary the carrier frequency around the nominal frequency. A drawback of this method is that this change is limited to the pass-band of the filters in the system. If multi-path exists in the system, delay will change with the carrier frequency. From the maximum to minimum delay change, the reflection factor can be deduced, and from the frequency difference between two maximums or minimam the length of the cable with the multi-path problem can be estimated **[10]**.

Results of the validation of the SATSIM system at NMi-VSL for an IF frequency scan range of (70±20) MHz are shown in following figures. Figure 5 shows a periodic delay change of nearly 4 ns peak to peak, which indicates clearly the mismatch and the resulting reflection (about 5%) in cable L (this is the cable from switch C to SATSIM and back to switch D; see Figure 4). The TX-RX delay (Figure 6) is the calibration value needed for TWSTFT. Its range of variation is –15 to –55 ns, so the TX-RX delay was
–35 ns with an uncertainty (95%) of ±20 ns. This is not satisfactory, so some measures were taken to avoid reflections in the cables to the SATSIM.

2.5 IMPROVEMENT OF THE VSL SATSIM SYSTEM

It is clear from the figures that a reflection exists at the IF input port of the mixer of the SATSIM. The SWR can be improved by placing an attenuator at the input of the mixer at the cost of higher needed power. Also an active device such as an amplifier can isolate the mismatch from the cable. The latter modification has been tested. The result is shown in the next section.

2.6 VALIDATION RESULTS OF THE VSL SATSIM SYSTEM AFTER MODIFICATION

The results of the modification are shown in the next figures. Some single point corrections due to a modem problem have been applied.

In Figure 7 the delay pattern of cable L is shown after modification of the SATSIM. A great improvement can be seen. No periodic pattern is recognizable any more and the delay variations are within ±0.5 ns, an improvement by a factor of 4, so this modification was effective.

The TX-RX delay (Figure 8) is the essential calibration value needed for TWSTFT. Its pattern is improved. Its range is now –38 to –60 ns, which is nearly half the original. The TX-RX delay is now –49 ns with an uncertainty (95%) of ±11 ns. This value is still not satisfactory.

2.7 SECOND IMPROVEMENT OF THE VSL SATSIM SYSTEM

It was found that, due to the chosen difference frequency DF-70 for the transfer of the 14 GHz TX signal to the 12.5 GHz RX signal of (1500 – 70 = 1430) MHz, the frequency sweep through the RX equipment during the calibration was opposite to that during the (Tx+Rx) measurement. So the zero cable delay correction for the Satre modem was not applied correctly. Now DF+70 was chosen: (1500 + 70 = 1570) MHz. The latter modification, which does affect the Tx-Rx calibration, has been tested.

2.8 VALIDATION RESULTS OF THE VSL SATSIM SYSTEM AFTER THE SECOND MODIFICATION

The results of the second modification are shown in Figure 9 and 10. The outlier in Figure 9 is a peculiarity of the modem used at that specific frequency; it does not affect the Tx-Rx result. Now in Figure 10 the Tx-Rx pattern is basically flat. This is satisfactory. The value of the TX-RX delay is now 27 ns with an uncertainty u_B of 2.3 ns (k = 2).

3 CONCLUSION

The calibration of a TWSTFT system using the SATSIM method has been performed. It has been validated for multi-path in cables due to mismatch to an uncertainty u_B of 2.3 ns (k = 2). Earlier, u_A has been determined as 0.1 ns for tau of 1 h to 50 d **[7, 8]**. TWSTFT can, thus, be calibrated in an absolute way using the SATSIM method independently from other calibration methods to a combined uncertainty u_C of 2.3 ns (k = 2).

4 ACKNOWLEDGMENT

5 REFERENCES

[1] **Guide to the Expression of Uncertainty in Measurement**, International Organization For Standardization (Geneva, Switzerland), ISBN 92-67-10188-9, first edition 1993, corrected and reprinted 1995.

[2] **Expression Of The Uncertainty Of Measurement In Calibration**, European Cooperation For Accreditation Of Laboratories, Publication Reference: EAL-R2, edition 1, April 1997.

[3] Rec. ITU-R TF.1153-1, 2001, *"The Operational Use Of Two-Way Satellite Time And Frequency Transfer Employing Pn Codes,"* ITU-R Recommendations, **Time Signals, and Frequency Standards Emissions**, Volume **2000**, TF Series (ITU Radio Communication Bureau, Geneva), ISBN 92-61-08851-1.

[4] G. de Jong and M.C. Polderman, 1995, *"Automated Delay Measurement System For An Earth Station For Two-Way Satellite Time And Frequency Transfer,"* in Proceedings of the 26th Annual Precise Time And Time Interval (PTTI) Applications and Planning Meeting, 7-9 December 1994, Reston, Virginia, USA (NASA CP-3302), pp. 305-318.

[5] G. de Jong, 1989, *"Accurate Delay Calibration Of Satellite Ground Stations For Two-Way Time Transfer,"* in Proceedings of the 3rd European Frequency and Time Forum (EFTF), 21-23 March 1989, Besançon, France, pp. 198-203.

[6] G. de Jong, 1990, *"Accurate Delay Calibration For Two-Way Time Transfer Earth Stations,"* in Proceedings of the 21st Annual Precise Time and Time Interval (PTTI) Applications And Planning Meeting, 28-30 November 1989, Redondo Beach, California, USA, pp. 107-116.

[7] G. de Jong, 1998, *"Delay Stability Of The TWSTFT Earth Station At VSL,"* in Proceedings of the 29th Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 2-4 December 1997, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 241-152.

[8] G. de Jong, 1998, *"Delay Stability Of The TWSTFT Earth Station At VSL,"* in Proceedings of the 12th European Frequency and Time Forum (EFTF), 10-12 March 1998, Warsaw, Poland (Tele & Radio Research Institute, Warsaw), pp. 175-181.

[9] F. G. Ascarrunz, T.E. Parker, and S. R. Jefferts, 1999, *"Group-Delay Errors Due To Coherent Interference,"* in Proceedings of the 1999 Joint Meeting of the European Frequency and Time Forum (EFTF) and the IEEE International Frequency Control Symposium, 13-16 April 1999, Besançon, France (IEEE Publication 99CH36313), pp. 198-202.

[10] G. de Jong, 2000, *"Precise Time Transfer,"* in Proceedings of the Asia-Pacific Workshop on Time and Frequency, 31 October-2 November 2000, CRL Tokyo, pp. 13-22.
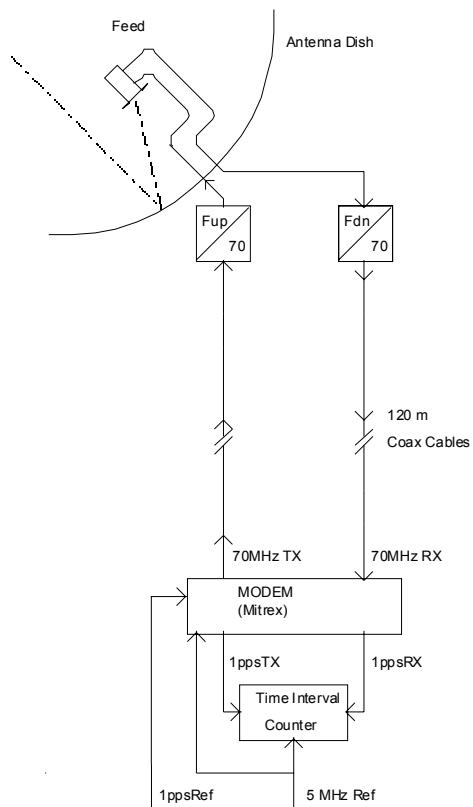
Figure 1. Typical TWSTFT setup.
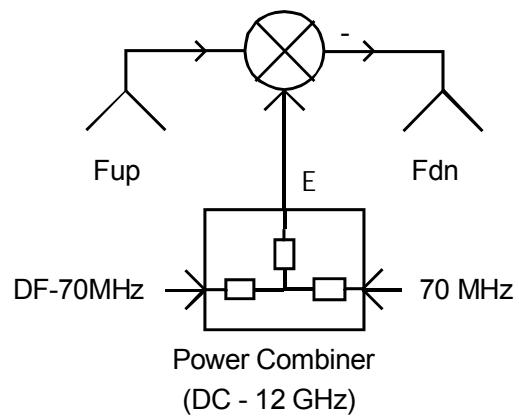
Figure 2. SATSIM calibration satellite simulator.
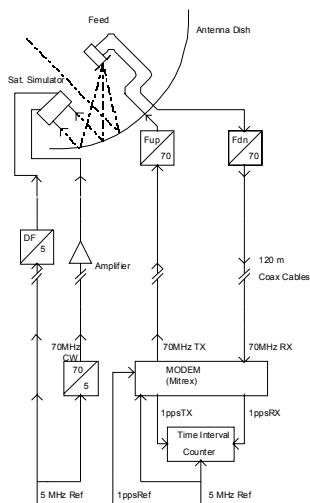
Figure 3a. Measurement of RX + TX delay.
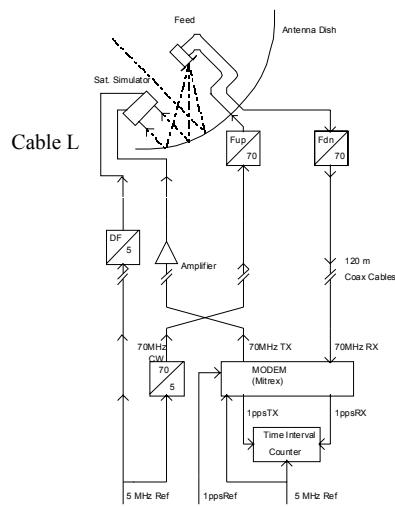
Figure 3b. Measurement of CAL + RX delay.
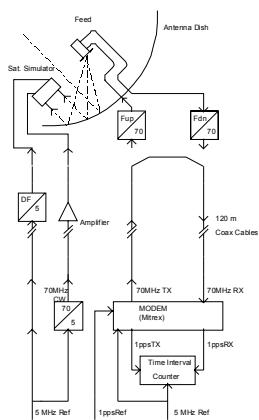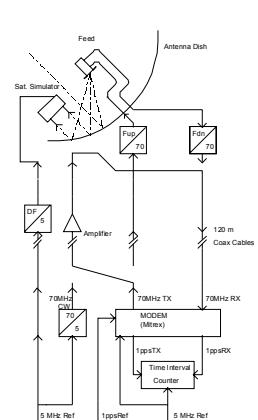
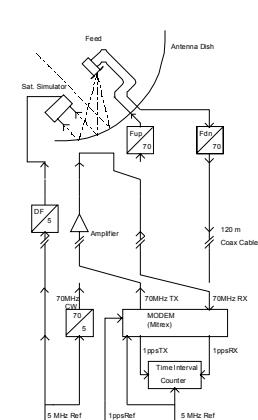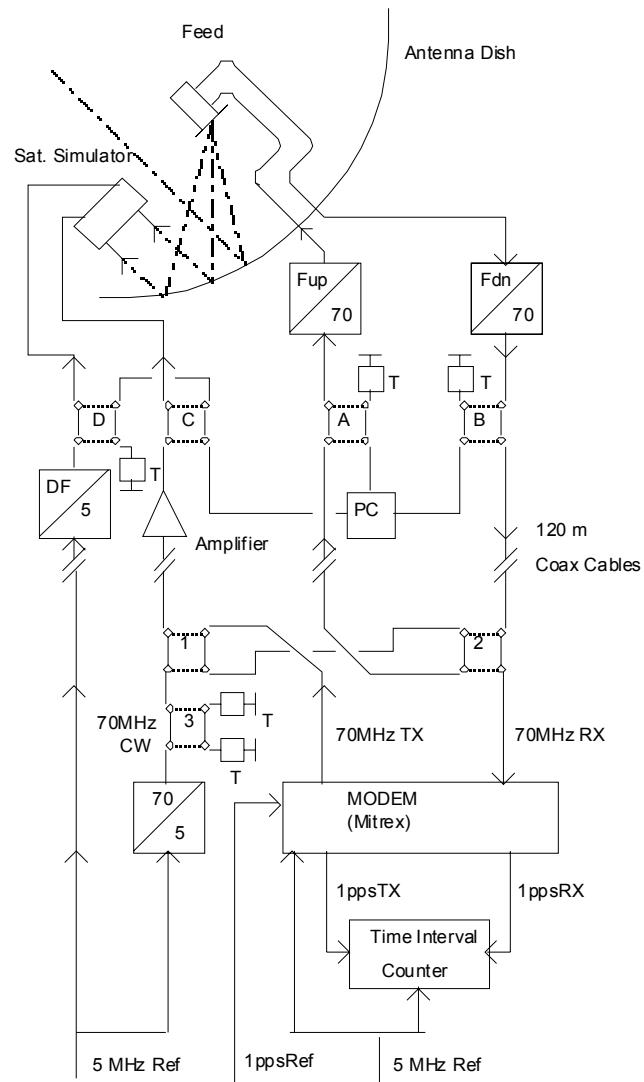Figure 3c. Cables A + B.   Figure 3d. Cables C+A.   Figure 3e. Cables C+B.

Figure 4. Automated SATSIM calibration system.

L   MJD52227
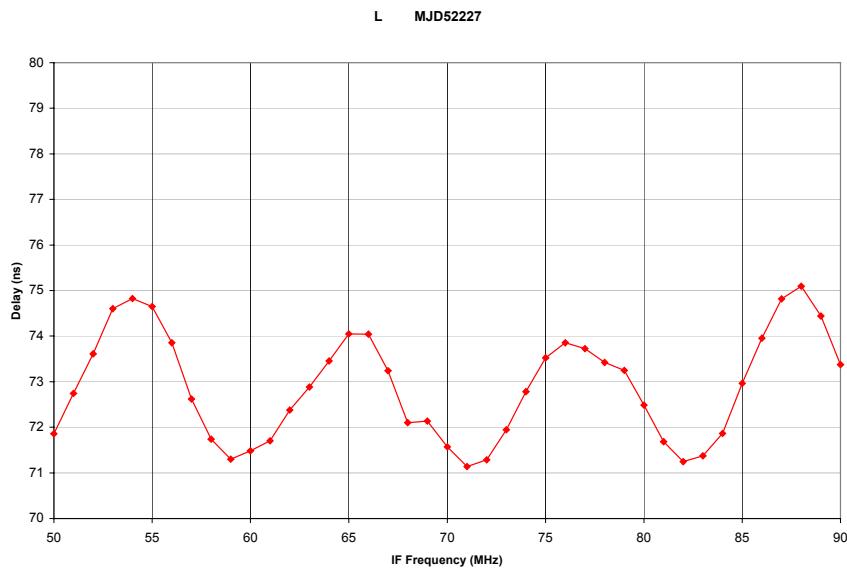
Figure 5. Delay cable L (= (C+B+L) – (C+B)).

TX-RX delay MJD 52227
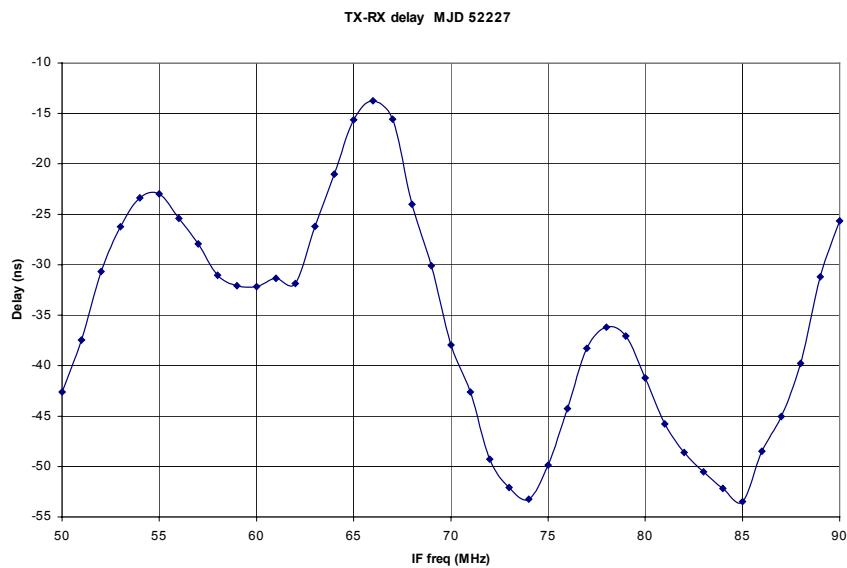
Figure 6. TX-RX delay.
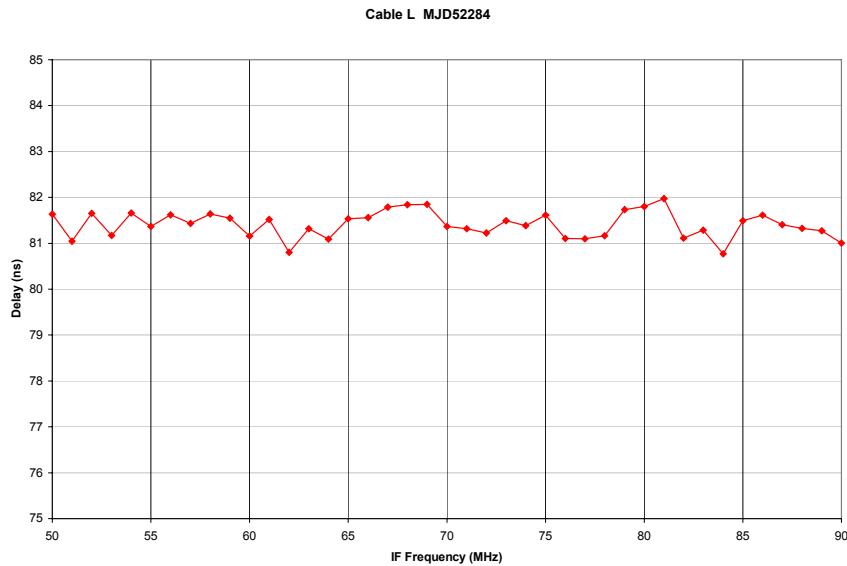
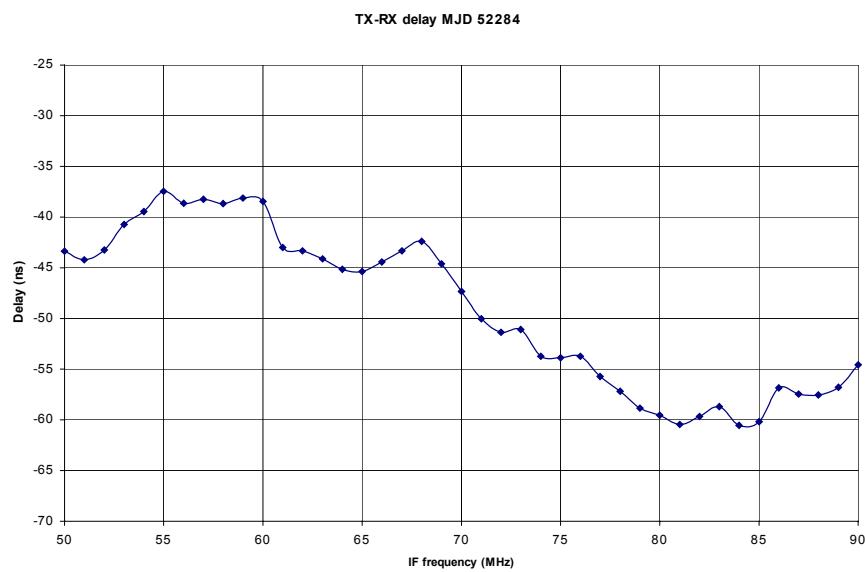Figure 7. Delay of cable L after improvement of the SATSIM.

Figure 8. TX-RX delay after improvement of the SATSIM.

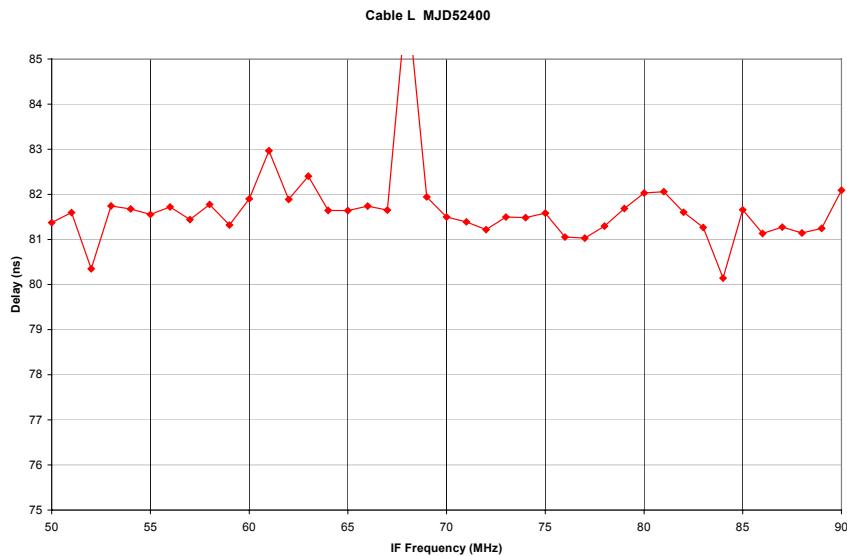Cable L MJD52400

Figure 9. Delay of cable L after second improvement.
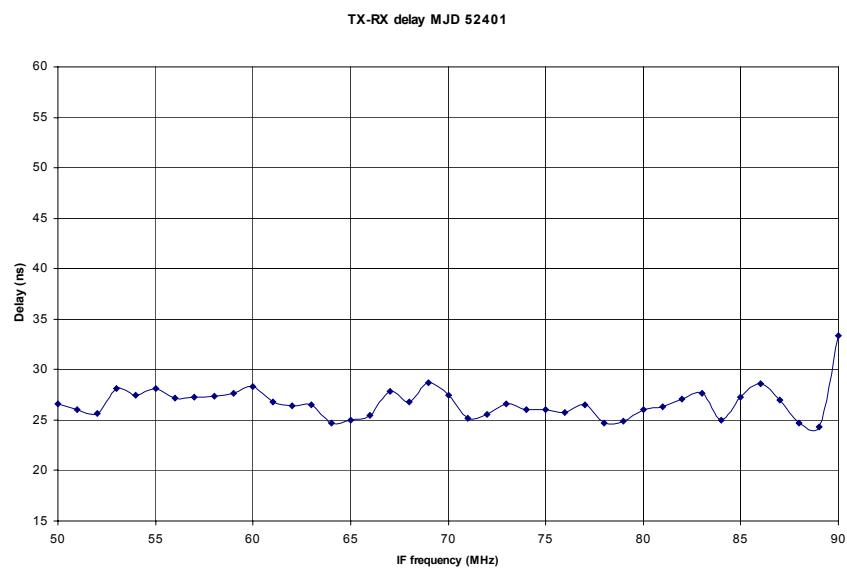
TX-RX delay MJD 52401

Figure 10.   TX-RX delay after second improvement.

QUESTIONS AND ANSWERS

JIM ROMBERG (Boeing): Are we reaching a limitation here on our accuracy by our inability to calibrate more accurately? What is your feeling on that?

GERRIT de JONG: I think this method is a good method, but you can already see that there are some problems with the modem. There is apparently some pattern sometimes in the modem itself. So the remaining peaks – I have sent my modem back to the manufacturer, it may be that those peaks can be lowered, and we will repeat the measurement when we get the modem back.

But the absolute uncertainty for two-way time transfer depends on the calibration. And this is one method. Another method is to send an earth station from one place to the other and use that as kind of a transfer standard. But in principle and theory, that is not needed if you are able to measure your instrumentation delays at your side and at the other side, and use the RX minus TX delay. If you know that, then you can solve the whole equation without a need to further solve it.

But yes, this way of calibration should be reliable and trusted. Of course, it is good to have this way with the SATSIM method to also check it with a portable station comparison. It was done in 1995, but the cells were not so good for the moving station at that time. But then we already saw, within 10 nanoseconds, agreement between the two methods. But there was still this break in it that we only detected last year.

BILL KLEPCZYNSKI Innovative Solutions International): I would like to make the comment that the two-way satellite working group from the CIPM, at the BIPM and CCTF, is going to try to evaluate some proposals for making calibration trips of two-way on a continuing basis. This afternoon we will discuss that a little bit more.

But yes, it is a problem which we are always concerned with and always working on. And this is some of the initial steps, and I think now in the next few years, they will probably drive some of these numbers even lower and lower in the future. How, I don't know exactly. But that is the way science and technology work.