ONE-WAY GPS TIME TRANSFER 2000

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Abstract

On 1 May 2000, the White House issued a Presidential directive for the Global Positioning System (GPS) to turn off Selective Availability (SA) on 2 May 2000. For nearly a decade, authorized user performance of one-way synchronization via GPS has improved every single year. This paper provides an annual assessment of how well the Global Positioning System can predict and disseminate UTC (USNO) to these specified users, based on data generated and processed by the United States Naval Observatory (USNO). And, because the recent Presidential directive now permits civilian timing users to exploit nearly the same, impressive time transfer accuracy of GPS, these annual metrics now offer a fairly representative performance assessment for both military and civilian timing users.

INTRODUCTION

Many worldwide users of precise time utilize "one-way" GPS time transfer, also known as "direct-access" GPS time transfer. In the direct-access GPS technique, a user can access a globally available common time reference, UTC(GPS) [1], by employing only one receiver and taking advantage of the available information in the broadcast GPS navigation message [2]. UTC(GPS) is GPS's real-time prediction of UTC as maintained by USNO, known as UTC(USNO), and UTC(GPS) is traceable to UTC(USNO). Empirically, this traceability has recently been at the 6-7 ns (1 sigma) level. The worldwide availability of UTC(GPS) satisfies the intent of both Presidential and congressional mandates to actively promote GPS as a global standard [3,4].

Direct-access GPS time transfer is mandated by the Master Positioning, Navigation and Timing Plan, [CJCSI 6130.01b] as the primary means for all Department of Defense (DoD) systems to access precise time [5]. Direct-access offers advantages over point-to-point time transfer techniques (GPS common view and Two-Way Satellite Time Transfer) that are most useful for military or military-related systems. Though point-to-point techniques are suitable for high accuracy applications, direct-access GPS time transfer doesn't require station-to-station communications between users and other ground receiver systems. Thus, direct-access GPS users can operate autonomously, in anonymity. Direct-access GPS

[1] The terminology "UTC(GPS)" is inconsistent with internationally accepted timing nomenclature in which the abbreviation in parentheses following "UTC" is meant to refer to a timing laboratory that contributes clock data to the formation of the international standard UTC(BIPM) and is steered to UTC(BIPM). The clocks used to create the independent GPS time scale are not used in the formation of UTC(BIPM) and GPS timing information is steered to UTC(USNO). The terminology "UTC(GPS)" used by the authors does not appear in U.S. Air Force documentation. –the Editor

time transfer has become a significant service for a diverse array of both military and civilian applications.

The United States Naval Observatory (USNO) performs around-the-clock monitoring of the GPS broadcast of time. USNO monitors three main time scales/references: 1) individual satellite time, 2) GPS ensemble time (the GPS Composite Clock), and 3) UTC(GPS). USNO currently employs keyed dual-frequency (L1 and L2) receivers, capable of tracking P(Y)-Code, to perform this monitoring function. USNO forwards daily time transfer information, gathered and processed from these receivers, to the GPS control segment, which is operated by the 2d Space Operations Squadron (2 SOPS). 2 SOPS, in turn, uses these USNO data to, among other purposes, keep UTC(GPS) aligned with, and traceable to, UTC(USNO).

As many know, not all GPS time transfer receivers are key-able, and therefore, not all GPS receivers can track P(Y)-Code. These civilian, or "unauthorized," receivers may not realize the same performance that keyed, or "authorized," sets benefit from. In particular, since the granularity of the civilian C/A-Code is a factor of ten worse than P(Y)-Code, some civilian users may experience slightly less accuracy than military users; however, some manufacturers have, for the most part, overcome this accuracy reduction with digital tracking algorithms. Also, the inability to track P(Y)-Code can translate into the unavailability of dual-frequency ionosphere measurements; however, techniques, such as codeless dual-frequency, exist to produce ionospheric measurements that are almost as good as those produced by pure dual-frequency code tracking.

Additionally, users who choose to augment GPS receiver systems with atomic frequency standards and all-in-view processing techniques can realize even further improved performance. This paper exclusively reviews the recent performance of direct-access GPS time transfer for *authorized* users in a fixed [surveyed] location scenario.

CURRENT TIME TRANSFER PERFORMANCE

Figure 1 shows a plot of the daily UTC(GPS)-UTC(USNO) time transfer root-mean-square (RMS) and average (AVGERR) errors for January 1999 through September 2000. This metric essentially indicates how well GPS is predicting and delivering precise time for the DoD. During this period, the time transfer was 6.32 ns RMS. That is, a fixed-location authorized user, tracking one satellite at a time, typically obtained DoD precise time with an accuracy of about 6.32 ns, 1 sigma. These numbers will not necessarily represent typical error figures for all users, particularly if certain users operate unauthorized receivers, have significant surveyed location biases or calibration errors, or experience unusual problems with multipath, troposphere modeling, or environmental stability.

Numerous enhancements at both the GPS Master Control Station (MCS) and USNO have contributed to this level of performance, well below the UTC(GPS)-UTC(USNO) budget total of 28 ns (1 sigma), listed in the USNO/2 SOPS interface control document, ICD-GPS-202 [6]. The GPS Program Office is currently reviewing documentation related to this error budget. Recently, USNO agreed to reduce its Measurement calibration uncertainty allocation from 12 ns (1 sigma) down to 3 ns (1 sigma) [7]. Assuming the other contributing error budget components remain unchanged, this USNO change would drop the overall error budget from 28 ns (1 sigma) to 25.5 ns (1 sigma) [8]. See Figure 2.

GPS-UTC(USNO) PERFORMANCE

A critical element in the delivery of UTC(GPS) to users is the GPS timescale, called the GPS Composite Clock, labeled herein simply as GPS. Typically, direct-access GPS time transfer users obtain satellite time by locking onto a broadcasting GPS vehicle, subsequently obtain GPS time by correcting for satellite clock offsets in subframe 1 of the navigation message, and finally obtain UTC(GPS) by applying GPS-UTC(USNO) corrections in subframe 4, page 18 of the navigation message. [2].

The stability of GPS-UTC(USNO) significantly affects the performance of UTC(GPS)-UTC(USNO), and usually serves as a second indication of how well GPS is delivering precise time. The daily GPS-UTC(USNO) offsets, corrected for leap seconds, for January 1999 through September 2000, are displayed in Figure 3. GPS remains well within ICD-GPS-200's specification for |GPS-UTC(USNO)|, 1000 ns, corrected for leap seconds [2].

It is important to note that, contrary to popular opinion, GPS time ***was never designed*** to represent the DoD's precise time source, UTC(USNO). Rather, GPS time serves as a stable timescale ***internal*** to GPS. For this reason, GPS time is not tightly synchronized to UTC(USNO). Instead, the MCS steers GPS time only to keep its offset from UTC(USNO), corrected for leap seconds, within the limits of the 1000 ns specification. GPS time steering is currently significantly below the noise level of GPS time itself, over satellite upload prediction spans. With this level of steering, the MCS is easily able to meet the 1000 ns specification without significantly degrading the stability of GPS time. By the way, users who want GPS's closest prediction of UTC(USNO) should make use of UTC(GPS), obtained by using the timing information in subframe 4, page 18.

GPS TIMESCALE STABILITY

The stability of |GPS-UTC(USNO)|, based on daily GPS-UTC(USNO) data points provided by USNO from October 1999 through September 2000, is presented in Figure 4. The 1-day stability for 2000, 1.53 E-14, is consistent with typical performance demonstrated in recent years.

Note how the Allan deviation slope gradually changes to -1 at a tau value of around 10 days, indicating the finite bounding of GPS-UTC(USNO). Additionally, note that the effective instability caused by GPS steering, at most, *never* approaches the inherent noise level of GPS-UTC(USNO) for tau = 1 day. One-day stability is especially important, since 1 day is the nominal GPS navigation upload prediction span. These indicators again demonstrate the effectiveness of GPS's time steering algorithm—long-term synchronization at a very small sacrifice to short-term stability.

Also shown within the same figure is a plot of the stability of UTC(GPS)-UTC(USNO), showing the superior long-term (tau > 1 day) stability of UTC(GPS) as compared to GPS time, highlighting a difference between the purposes of GPS time and UTC(GPS). GPS time is designed for stability over nominal satellite upload prediction spans (0-24 hours); UTC(GPS) is designed to deliver a prediction of UTC(USNO). The superior long-term stability of UTC(GPS) as compared to GPS time is a byproduct of this design. However, UTC(GPS) does exhibits inferior short-term (tau < 1 day) stability as a result, because of the additional uncertainty of the subframe 4, page 18 time transfer parameters.

NEAR-TERM ENHANCEMENTS

Under current operations, 2 SOPS downloads USNO-generated time transfer information once per day, shortly after 1500 UTC. 2 SOPS utilizes a 486-based computer, connected to a voice phone configured as a modem, and software written in-house. This current setup is not officially integrated into the MCS architecture, and therefore has no maintenance support or configuration control/management. Given the criticality of GPS's time transfer mission to the world, the community is currently pursuing the establishment of a more formal interface between USNO and the MCS.

Several agencies, including the GPS Program Office, the Aerospace Corporation, 2 SOPS, USNO, and the National Imagery and Mapping Agency (NIMA) have recently participated in technical discussions of possibilities for formalizing a USNO-MCS data transfer interface. The discussions have covered possibilities that would make use of the SIPRNET secure network and/or existing communication lines between USNO, NIMA, and the MCS, to pipe USNO data into the MCS in near-real time.

The establishment of a near-real-time data interface between USNO and the MCS opens up possibilities for optimizing GPS-UTC(USNO) predictions in the MCS. Under current operations, the MCS predicts GPS-UTC(USNO) using the two most recent daily estimates of GPS-UTC(USNO), generated by USNO using a least-squares fit on a 37-hour batch of individual satellite tracks based on broadcast parameters.

Were the MCS, in the future, to obtain the individual tracks in near-real time, the MCS would experience major benefits. In particular, near-real-time transfer of these satellite tracks would permit the MCS the ability to apply corrections for known observables in MCS files, which are, in particular, the MCS Estimated Range Deviations (ERDs). Applying these corrections would refine the quality of individual satellite tracks by removing known broadcast errors. The MCS would, in turn, send these refined tracks into a two-state Kalman filter designed to optimize estimation and prediction, tailored for the noise types and levels inherent to the system. In essence, optimized estimation and prediction of GPS-UTC(USNO) means that each satellite upload would have the most current, and accurate parameters in subframe 4, page 18 of the navigation message. Translation—an optimization of GPS's delivered prediction of UTC(USNO). See Figures 5 and 6.

Additionally, near-real time data availability would permit around-the-clock direct access GPS time transfer performance monitoring. The MCS monitors satellite ranging performance around the clock, it does not currently have the ability to similarly monitor time transfer or GPS timescale stability. A formalized, near-real time data interface between USNO and the MCS would change this.

The security, documentation, programmatic, and support issues associated with the establishment of a formalized data interface are not insignificant. Ultimately, the community's realization of the critical dependence of GPS time transfer mission on the USNO-MCS interface will dictate the priority of establishing formality to this data interface.

LONG-TERM GOALS

In order to satisfy the intent of both Presidential and Congressional mandates to actively promote GPS as a global time standard [3,4], a change in the GPS time transfer paradigm must occur. The perception that GPS is a noisy transponder of UTC(USNO) must change. In reality, GPS provides an independent time scale [GPS time] and a prediction of the offset between GPS time and the DoD Master Clock. Because direct-access GPS time transfer users apply this predicted offset, broadcast in subframe 4, page 18, these users are, in effect, realizing UTC(GPS). The operational and hardware changes required to realize the vision of GPS as a distributed space-based clock are minimal. These changes will be documented in a follow-on paper which will be offered to the PTTI Manager, the GPS Joint Program Office, the Interagency GPS Executive Board and the National and International timing communities for their consideration. The goal of this dialog is to reach consensus on the roadmap and technical end states for GPS Time Transfer. These actions will be a part of on-going implementation of the GPS Presidential and Congressional direction to make GPS useful to civilian users around the world.

CONCLUSION

Worldwide civil and military applications are just beginning to realize the power and utility of GPS as a space-based common time reference. 2 SOPS and USNO, along with other agencies, have sustained the outstanding performance of UTC(GPS) and remain committed to improving GPS time transfer in the future. In the near term, the formalization and automation of the USNO-MCS data interface to an around-the-clock operation will enhance the integrity and performance of UTC(GPS). In the long term, many in the community anticipate that the Global Positioning System will gain acceptance worldwide as an independent, space-based distributed clock.

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REFERENCES

[1] The terminology "UTC(GPS)" is nontraditional in that the term in parentheses normally refers to a timing laboratory which contributes to the formation of international standard time UTC(BIPM). However, in the opinion of the authors, "UTC(GPS)" accurately reflects the fact that large numbers of users around the world are taking UTC time directly from GPS and this is leading to the use of GPS time as a convenient and distinct standard. In addition, promoting the use of GPS as a global standard for positioning, navigation, and timing is required by presidential policy, U.S. legislation, and international statements such as the U.S.-Japan Joint Statement on GPS.

[2] ICD-GPS-200, Revision C, 10 October 1993, IRN-200C-002, 25 September 1997.

[3] White House Fact Sheet, "*U.S. Global Positioning System Policy*," from the Office of Science and Technology Policy, National Security Council, 29 March 1996.

[4] United States Code, Title 10, Subtitle A, Part IV, Chapter 136, Section 2281, "Global Positioning System,", 27 January 1998.

[5] CJCSI 6130.01 b, "*2000 CJCSI Master Positioning, Navigation and Timing Plan*," 15 June 2000.

[6] ICD-GPS-202, Revision A, 13 December 1996.

[7] USNO-MCS Time Transfer Memorandum of Agreement, 2000.

[8] S. Hutsell, "*A Statistical Analysis Of The GPS Time Transfer Error Budget*," Proceedings of the 51st ION Annual Meeting, Colorado Springs, CO, 5-7 June 1995, pp. 421-428.

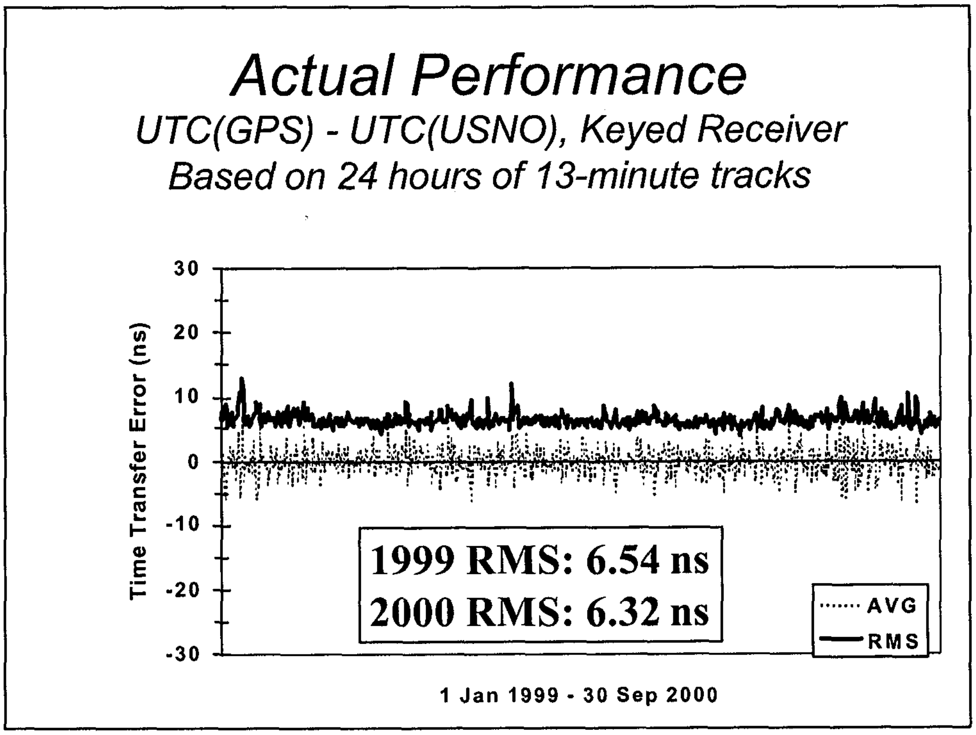

Figure 1. UTC(GPS) – UTC(USNO) Root Mean Square and Average Error

Time Transfer Error Budget

Fixed Location User (ns)

■ Component	Spec	PPS (Typical)
■ *<u>USNO Measurement</u>*	<u>3</u>	2-3
■ GPS Prediction	9.7	2-4
■ SV Component	20	5-7
■ User Component	12	2-5
■ Totals (RSS)	25.5	6-10

Figure 2. 2000 GPS Time Transfer Error Budget

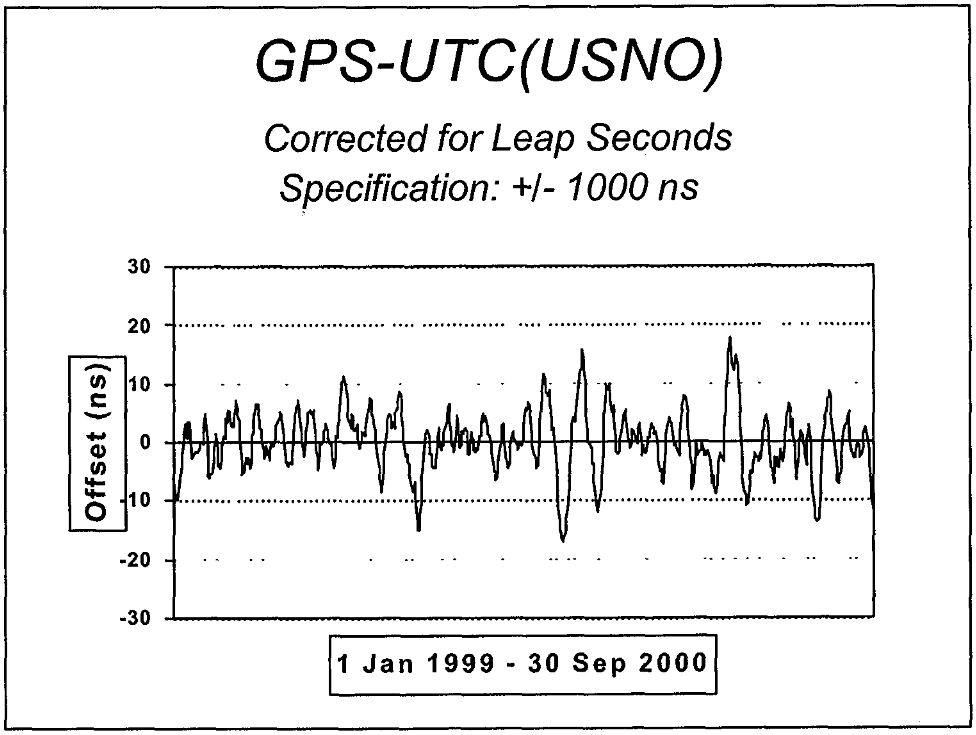

Figure 3. Daily GPS – UTC(USNO) Offset

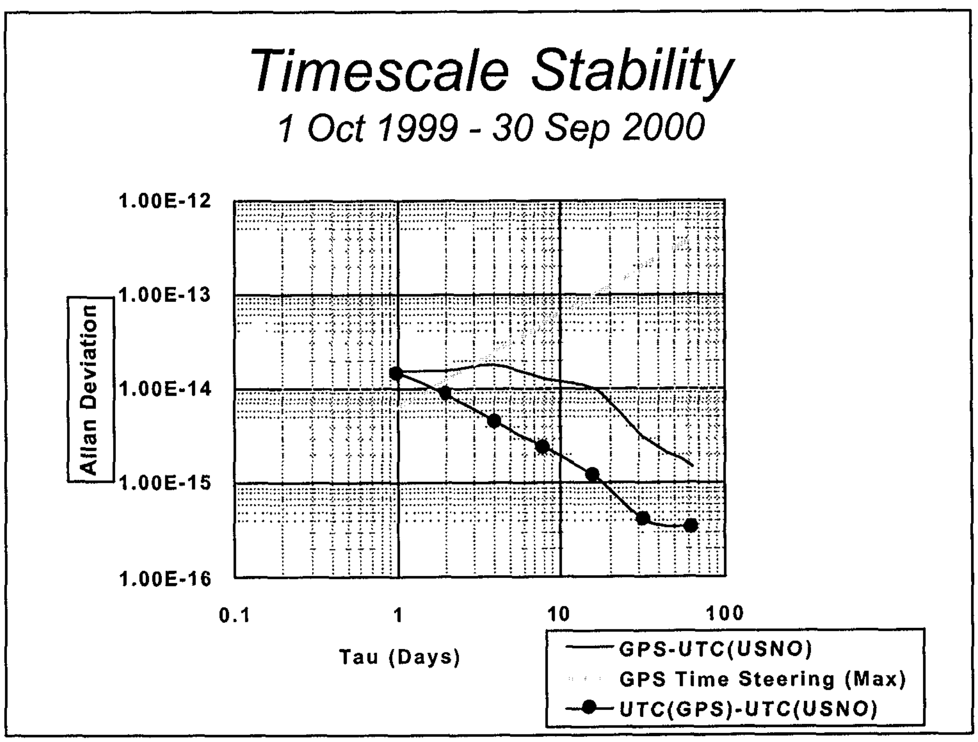

Figure 4. Timescale Stability: GPS Time vs. UTC(GPS)

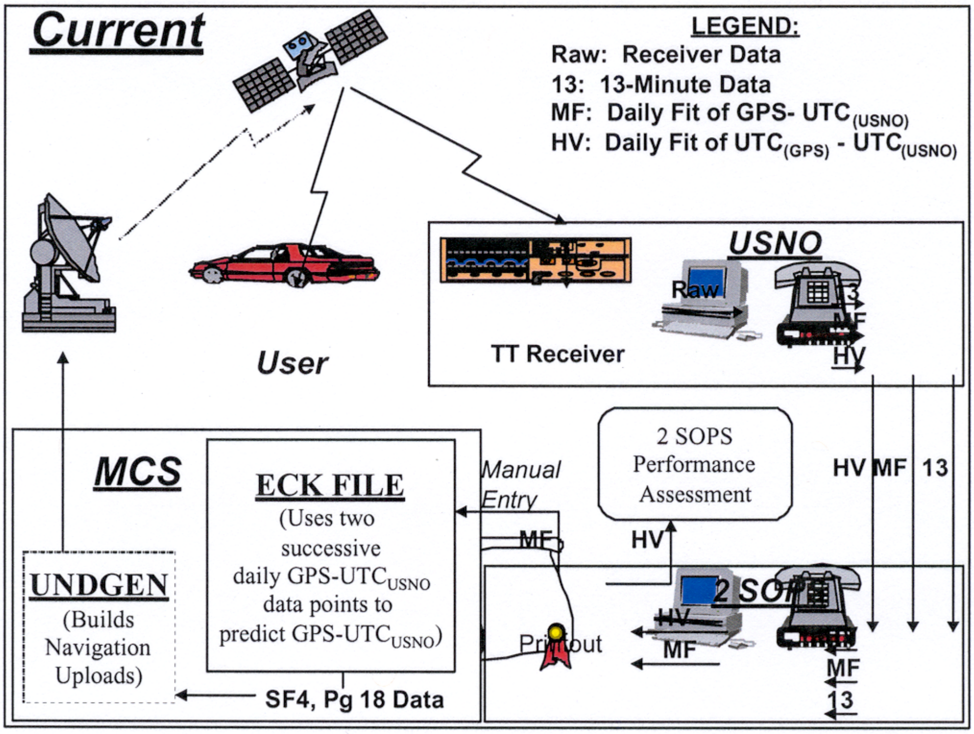

Figure 5. Current USNO – MCS Time Transfer Data Interface

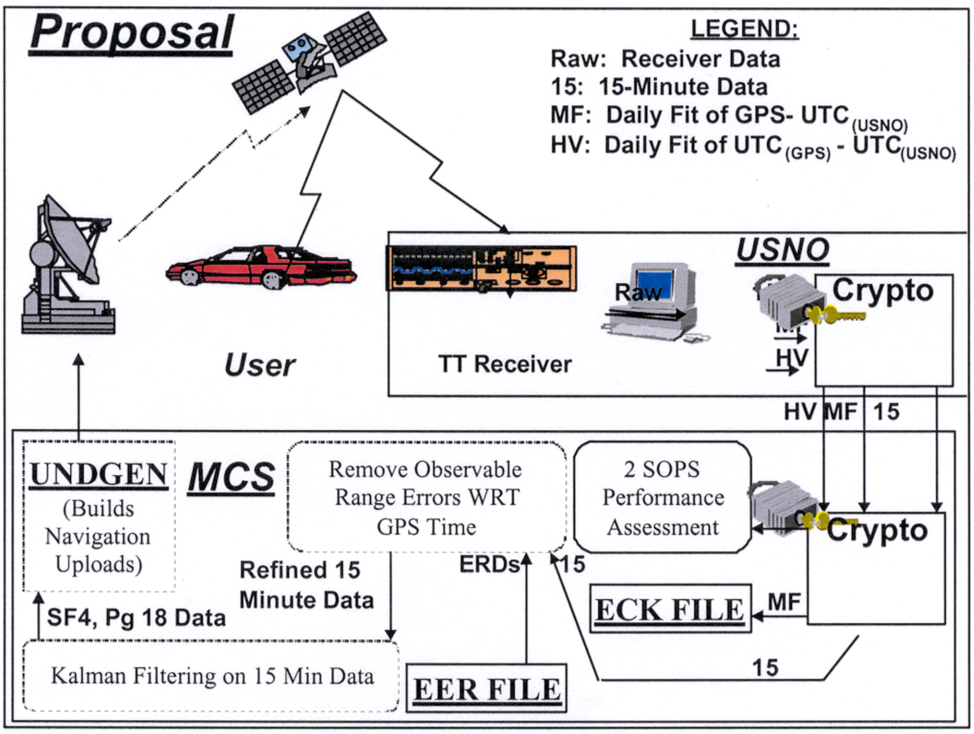

Figure 6. Proposed USNO – MCS Time Transfer Data Interface