FEEDBACK FROM GPS TIMING USERS: RELAYED OBSERVATIONS FROM 2 SOPS

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Abstract

Time-transfer users who make use of GPS for one-way synchronization benefit from being able to operate autonomously, and in anonymity. Though autonomous, anonymous operations can prove advantageous, in particular, for activities associated with the military, their anonymity can result in the undesirable side effect of lost connectivity with the GPS community. Recent GPS satellite maintenance activities have exposed some unusual characteristics of certain, but not all, types of GPS time-transfer receivers. As a result, many Department of Defense (DoD) and other government agency users affected by these satellite activities have emerged to provide the GPS community (2 SOPS in particular) with feedback concerning their experiences with GPS Time Transfer. This paper presents general descriptions of the types of users who have emerged, as well as general observations on the received feedback.

INTRODUCTION

The first GPS week rollover occurred recently, during the weekend of 21-22 August 1999. Prior to this event, the GPS Master Control Station (MCS) performed a number of rollover-related tests, including several on two GPS satellites. The combination of these tests and the actual GPS week rollover stimulated some dialogue between various GPS time-transfer users and personnel at the GPS control segment. The authors have gathered information from various communications with users into a summary of a) what kinds of problems GPS time-transfer users have experienced, b) what categories of GPS time-transfer users exist, and c) what specific missions make use of GPS for time transfer.

The PTTI Meeting has, in the past, exposed many civilian timing users of GPS. The authors have chosen to concentrate on Department of Defense (DoD) users in particular, in hopes of furthering the community's understanding of military systems that utilize one-way synchronization via GPS.

This paper is limited to only unclassified information and does not identify associations between specific user organizations, user equipment manufacturers, or operational problems encountered.

ROLLOVER TESTING

Prior to the actual GPS week rollover of 21-22 August 1999, the MCS, on several occasions, set vehicles unhealthy to permit testing and validation of various rollover events. These satellites, and their associated test times, were as follows: PRN27 (SVN27): 23, 25 April & 1, 27 May 1999; PRN13 (SVN43): 7-12 July 1999.

During these tests, the MCS simulated GPS Week rollover, 1999-2000 rollover, Leap Day 2000 rollover, and 2000-2001 rollover. These tests served the primary purpose of validating the MCS's ability to control and interface with GPS satellites during and after these respective rollovers. The MCS experienced no major problems during these tests and successfully demonstrated its preparedness for these rollovers.

User Results

However, communication with several users, during and after the above activities, gave clear indication that not all GPS user equipment works as one would desire.

In particular, user feedback further supports the common perception that many receiver systems don't sample the GPS navigation message's subframe 1 health information nearly as often as they perhaps should [1]. In fact, many receiver systems don't even look at subframe 1 health – instead, such receivers look only at the health summary information in subframes 4 and 5, in most cases no more than ***once per day***, from the broadcast of only ***one*** satellite. Typically, these receiver systems only update their stored health summaries upon observing an updated time of applicability (t_{oa}) from a broadcasting satellite.

This design can pose potential for numerous problems. Suppose a receiver treats its stored health summaries as truth, and tracks a satellite that, according to a previous day's download, is supposedly healthy, but isn't in reality. If that receiver system sees a new t_{oa}, and proceeds to download an almanac from this truly unhealthy satellite, that receiver system will likely store an invalid almanac. Moreover, if that invalid almanac contains [bogus] unhealthy settings for most or all of the constellation, this series of events could lead to the receiver system blindly deciding to not even ***attempt*** to track satellites. In this downward spiral, the receiver could render itself useless until an operator manually intervenes. Several users reported this exact scenario.

GPS WEEK ROLLOVER

On 21-22 August 1999, the GPS week rollover at the MCS occurred relatively uneventfully.

For users, the most recent version of ICD-GPS-200 Revision C addresses the GPS Week Rollover as follows: "At the expiration of GPS week number 1023, the GPS week number will rollover to zero (0). ***Users must account for the previous 1024 weeks.***" [2]. Not all users did.

User Reports

Thankfully, the number of problems experienced during and after GPS Week Rollover was less than many had predicted. Given the relatively higher proliferation of GPS user equipment for positioning-related missions, one would expect feedback from those missions to significantly overshadow the feedback from timing users. However, since timing users are generally more susceptible to date-related anomalies (for obvious reasons), the number of telephone calls and electronic mail messages to the MCS, from timing users experiencing problems, actually outnumbered those from positioning users encountering difficulties.

1. The most commonly reported problem involved a miscalculation of the GPS-UTC(USNO) correction term. In many cases, several receiver systems would mis-tag the reference time for these corrections (t_{ot}) by integral multiples of 256 weeks, most commonly 1024 weeks. In one particular instance, GPS satellites were broadcasting a GPS-UTC(USNO) rate offset of approximately 2.9 E-14 s/s. Given the current typical stability level of GPS time with respect to UTC(USNO), this magnitude was relatively benign. However, when user sets mis-propagated this rate offset by 1024 weeks, users experienced roughly 18 microseconds of error.

This problem cropped up roughly 48 hours before actual GPS week rollover, since many satellites began broadcasting t_{ot} values with week zero, a couple days prior to 22 August 1999. For receivers that were designed to offer performance with errors on the order of only tens of nanoseconds, 18 microseconds posed an unwelcome surprise for many.

2. Other receivers experienced similar difficulties with t_{oa}. Again, many users mis-propagated their downloaded almanac parameters by 1024 weeks. Obviously, a ~19.6 year mis-propagation of satellite orbit parameters can result in predicted satellite positions hemispheres away from truth. Under these circumstances, some user equipment generated incorrect look angles, and were therefore unable to lock onto the majority, if not all, satellites in view.

Several users were able to work around this problem by loading current almanacs with artificial t_{oa} parameters. This general type of problem seemed to surface more often in GPS mission planning software than in actual receiver equipment.

3. Some receiver engines simply were not able to handle the apparent ambiguity of the rollover, and lost lock on most or all satellites in view. Some receiver sets were able to recover on their own; some required manual intervention (resetting).

4. Because the output date of many receivers was (and is) off by about 19.6 years, many users chose to permanently disconnect their receivers from their respective systems, and freewheel on atomic frequency standards until such a time that they could replace their "out-of-date" equipment.

5. Many timing users choose to operate GPS receivers with manual tracking schedules, which require periodic updates. Some of these receivers display a defaulted date of entry on an interactive display panel, whereby personnel can enter schedule changes. Prior to the GPS week rollover, typically these receivers would default to the current date. After the rollover, however, some receivers began defaulting to dates that were not only on the wrong 1024 week cycle, but also off by several days from the correct modulo-1024 date. This situation, when understood, may be tolerated, with the help of the finesse and workarounds by adept mathematicians.

GPS TIME TRANSFER USERS

In addition to hearing about problems, GPS control-segment personnel were able to gain a better perspective about just what kinds of DoD missions make use of GPS for time transfer. In general, the authors interfaced with specific DoD users who operate communication systems, test ranges and research facilities, metrology and calibration laboratories, and surveillance platforms.

Communication Synchronization

In the PTTI community, when we hear the term, "communications," we immediately picture images of worldwide computer networks, NTP servers, and local area networks (LANs) [3]. In the military, many often associate the same term with satellite and landline systems that offer both clear and secure communications, for both voice and data transmissions. These capabilities exist thanks to systems such as the Defense Satellite Communications System (DSCS), the Defense Data Network (DDN), and the Defense Switch Network (DSN). The military also makes use of commercial communication systems, such as cellular phone and pager devices, which, to a large extent, rely on multiple ground stations, tied together and synchronized via GPS.

At the heart of the communications capabilities for the DoD is the Defense Information Systems Agency (DISA). DISA's charter is, "To plan, engineer, develop, test, manage programs, acquire, implement, operate, and maintain information systems for C4I and mission support under all conditions of peace and war." [4].

One satellite system responsible for providing assured, jam-resistant and secure communications for warfighters is MILSTAR, operated by the 4th Space Operations Squadron, Schriever AFB, CO [5]. MILSTAR satellites are designed to house four redundant rubidium frequency standards, which maintain satellite time. The MILSTAR Satellite Mission Control Subsystem (SMCS) periodically synchronizes their respective satellite times to MILSTAR time, maintained using commercial cesium frequency standards, housed within the SMCS. The SMCS ties MILSTAR time to UTC(USNO), using, not surprisingly, GPS [6]. See Figure 1.

The use of GPS for precise synchronization of satellite communications is by no means uncommon in the DoD. ***Even the ground antennas that the Master Control Station employs to command and control GPS satellites use GPS timing receivers***!

Research, Development, and Testing

Several test ranges require stable timing for precise analyses of numerous forms of data collected at various stations on their respective ranges. Both White Sands Missile Range (WSMR), New Mexico, and the Eastern Range (ER), Florida, have presented papers at recent PTTI meetings [7].

One unique type of research activity within the DoD involves ionospheric data collection and analysis. The U.S. Navy currently sponsors the High Frequency Active Auroral Research Program (HAARP), a scientific endeavor aimed at studying the properties and behavior of the ionosphere. HAARP, located at Gakona, AK, places particular emphasis on being able to employ this science to enhance communications and surveillance systems for both civilian and defense purposes. Amongst a variety of equipment located at HAARP are Vertical Incidence Sounders (or Ionosondes), employed to help characterize the ionosphere [8]. See Figure 2.

An ionosonde transmits a short duration, single frequency signal upward toward the ionosphere. The ionosonde receiver, connected to a GPS timing receiver, listens for the returning signal, reflected from the overhead ionospheric layers. The time delays of the returned signals help to determine the "virtual heights" of the respective layers.

A common term associated with ionosondes is DISS, which stands for Digital Ionosonde Sounding System. The 55th Space Weather Squadron, at Schriever AFB, CO, makes use of data from over 70 DISS sites worldwide [9,10].

Metrology and Calibration

The Air Force, Army, Navy, and Marine Corps all operate base laboratories to calibrate various types of equipment used for numerous types of weapon systems [11].

One unique calibration activity operates at the Algonquin Radio Observatory, in Canada. A lesser-known mission of GPS is the Nuclear Detonation (NuDet) Detection System, or NDS, which makes use of payloads aboard GPS satellites to pinpoint and time-tag nuclear detonations. A GPS Joint Program Office-sponsored activity makes use of a 150-foot antenna at Algonquin to facilitate NDS calibration. As with most calibrations involving line-of-sight transmission of radio waves, this NDS calibration activity requires very precise timing. This Algonquin activity, not surprisingly, uses GPS. Interesting is how one mission of GPS (NDS) makes use of another mission of GPS (time transfer), in order to optimize performance [12].

Another activity dependent on precise time-tagging is the Atlantic Undersea Test and Evaluation Center (AUTEC) located on Andros Island, Bahamas, operated by the Naval Undersea Warfare Center. AUTEC is a deep-water test and evaluation facility for making underwater acoustic measurements (using hydrophones), testing and calibrating sonars, and providing accurate tracking data on various weapon systems. Most tests conducted at AUTEC require meter-level underwater tracking. Precise calibration is essential to meeting this goal. AUTEC presented a paper at PTTI '92 describing their use of GPS time transfer for calibration [13].

Surveillance—Event Time Tagging

Synchronized DoD surveillance systems permit analysis centers the capability to constructively combine multiple sources of coherently time-tagged observations. Such DoD surveillance systems reside in the air, on the ground, in the ocean, and in space.

The Air Force operates a variety of ground-based sensors that forward critical space surveillance information to the NORAD complex inside Cheyenne Mountain, CO. These include the likes of missile warning radars, such as the PAVE PAWS sites at Cape Cod AFS, MA and Beale AFB, CA. See Figure 3. Other sensors include the likes of the AN/FPS-85 near-earth and deep-space tracking radar at Eglin AFB, FL, as well as the passive space surveillance site at Misawa Air Base, Japan [14]. Precise time tagging is essential for tracking objects in space, as precise orbit determination is critical to, for instance, determining whether an object is going to collide with another space object, or re-enter the atmosphere.

Clearly, error-free time-tagging is critical to the aerospace defense of North America. All of the above sites make use of GPS for timing.

The Air Force also operates a Space-Based InfraRed [Warning] System, called SBIRS, which detects and tracks missile and space launches [15]. As with ground-based surveillance systems, observation time-tagging is necessary for SBIRS tracking precision. The SBIRS program employs GPS receivers at their ground stations. See Figure 4.

Surveillance—TDOA and FDOA

As mentioned earlier, GPS houses a lesser-known payload called NDS. A basic principle of NDS involves the ability of NDS sensors on multiple GPS satellites to simultaneously observe a single NuDet. By utilizing a synchronized time reference (GPS time), NDS is able to calculate multiple time-difference-of-arrival (TDOA) values to geometrically pinpoint the location of a NuDet with high precision. This use of multiple sensors, separated by large distances, for geometric location of emissions, is a common theme in many DoD surveillance architectures. See Figure 5. Precise platform-to-platform synchronization is the key to accuracy for TDOA-based surveillance systems, as well as those employing frequency-difference-of-arrival (FDOA) techniques.

For reasons that are self-evident, NDS payloads aboard GPS satellites don't need to utilize GPS receivers in order to obtain precise synchronization. However, obviously, other TDOA and FDOA surveillance platforms can and do greatly benefit from the globally available DoD time reference. This is why many TDOA and FDOA surveillance systems use GPS today.

Perhaps the best known airborne surveillance platform that makes use of TDOA is the RC-135. Based on the Boeing 707 airframe, the RC-135 is the workhorse of several airborne surveillance platforms, including Rivet Joint, Cobra Ball, and Combat Sent. See Figure 6. Collectively, these RC-135 programs ***desire*** accuracy on the order of 1 ns [16].

One very interesting ground-based system that performs geometric location calculations is Naval Space Command's Space Surveillance System. See Figures 7 and 8. Once called NAVSPASUR, this system consists of three transmitter and six receiver sites over the Southern United States. The three combined transmitter sites radiate all observable near-earth orbiting man-made objects that cross over the continental U.S. The six receiver sites attempt to pick up returns from these objects. The use of multiple receiver stations permits this surveillance system to geometrically locate where (and when) a near-earth space object is crossing over the U.S. The better the synchronization between receiver stations, the more accurate the observations and, therefore, the more precise the orbit determinations. The Naval Space Command's Space Surveillance System uses GPS [17].

The Navy also operates a network of underwater hydrophone arrays connected by undersea cables to shoreline facilities. This Navy SOund SUrveillance System (SOSUS) combines readings from multiple arrays to "hydrolocate" various sources of emissions. Utilizations of SOSUS have included Naval deep ocean surveillance, seismic monitoring, and marine mammal tracking [18].

OBSERVATIONS

The DoD makes use of GPS time transfer in more ways and applications than most people realize. All of the above-mentioned systems benefit from accurate ***relative*** time synchronization, a feature globally offered with excellent accuracy by GPS.

This year's communication with GPS time-transfer users has also exposed a perhaps less encouraging pattern within the DoD--the proliferated use of unkeyed/unauthorized receivers. Many DoD users assert that because SPS signal service accuracy is sufficient for their requirements, they therefore have no requirement to correct for selective availability (SA). However, many users don't fully appreciate (and some are not even aware of) the desirability and necessity of GPS's Anti-Spoof (AS) feature, which is only available to users with authorized [keyed] user equipment.

Additionally, the feedback from users identifying problems with their GPS user equipment reminds us how different manufacturers vary in their perseverance of making the best use of the GPS navigation message, and of ICD-GPS-200.

Perhaps the most disconcerting observation the authors have noted during recent communications with users is the general, overall gap in connectivity between the GPS community as we know it, and the somewhat autonomous, anonymous world of DoD GPS time-transfer users. The authors hope, through efforts such as this paper, to stimulate improved connectivity in the future.

CONCLUSION

One-way time-transfer synchronization, via GPS, is ***integral*** to the Department of Defense. With few exceptions, the performance of virtually every DoD activity either directly or indirectly benefits from the global, highly accurate time-transfer service provided by GPS.

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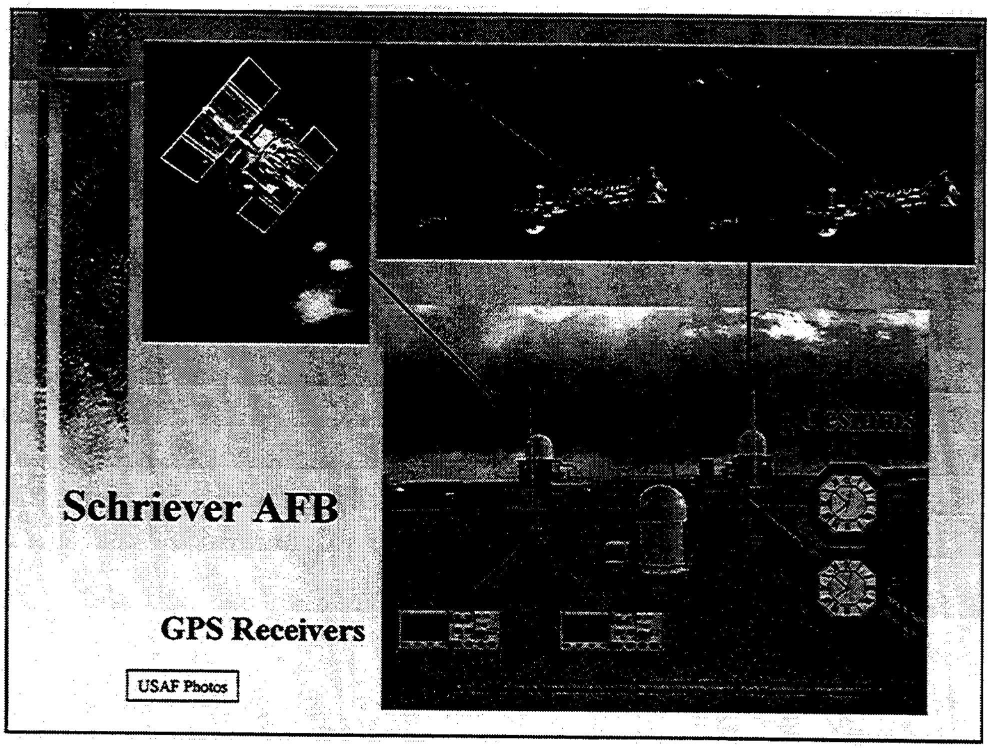

Figure 1. MILSTAR Synchronization via GPS

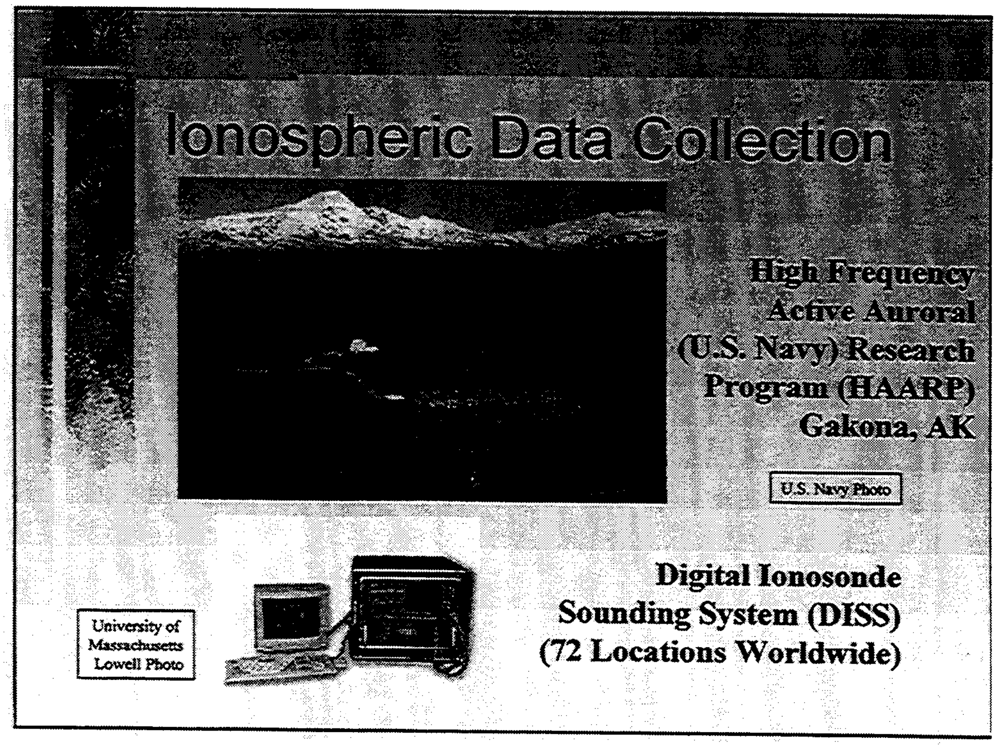

Figure 2. Ionospheric Research Systems

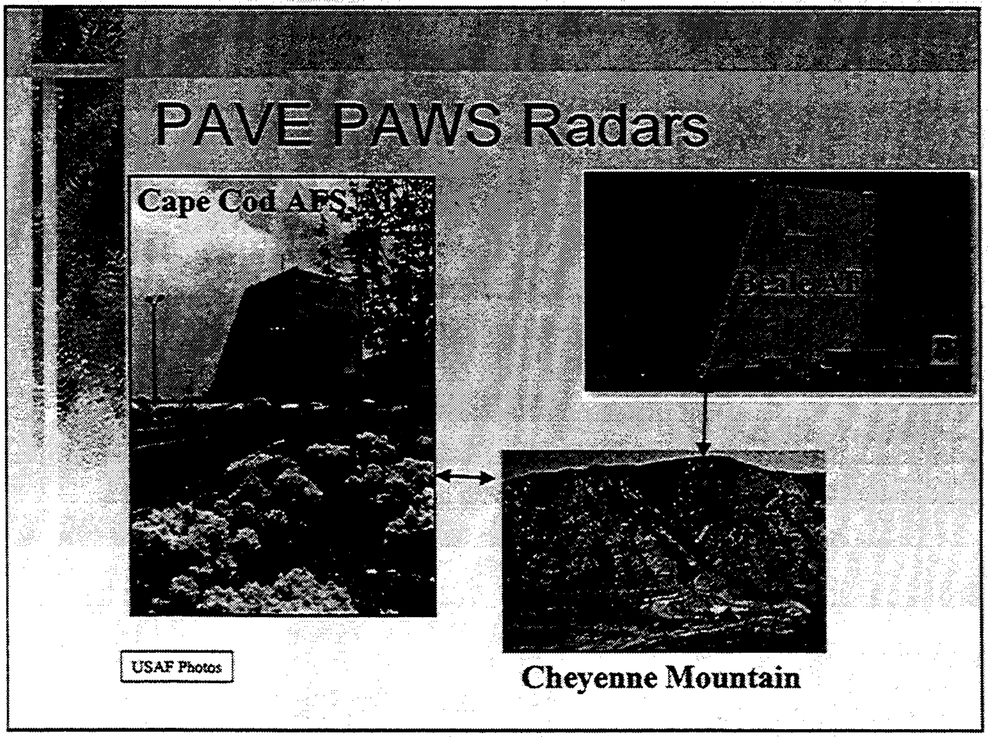

Figure 3. Missile Warning Radars

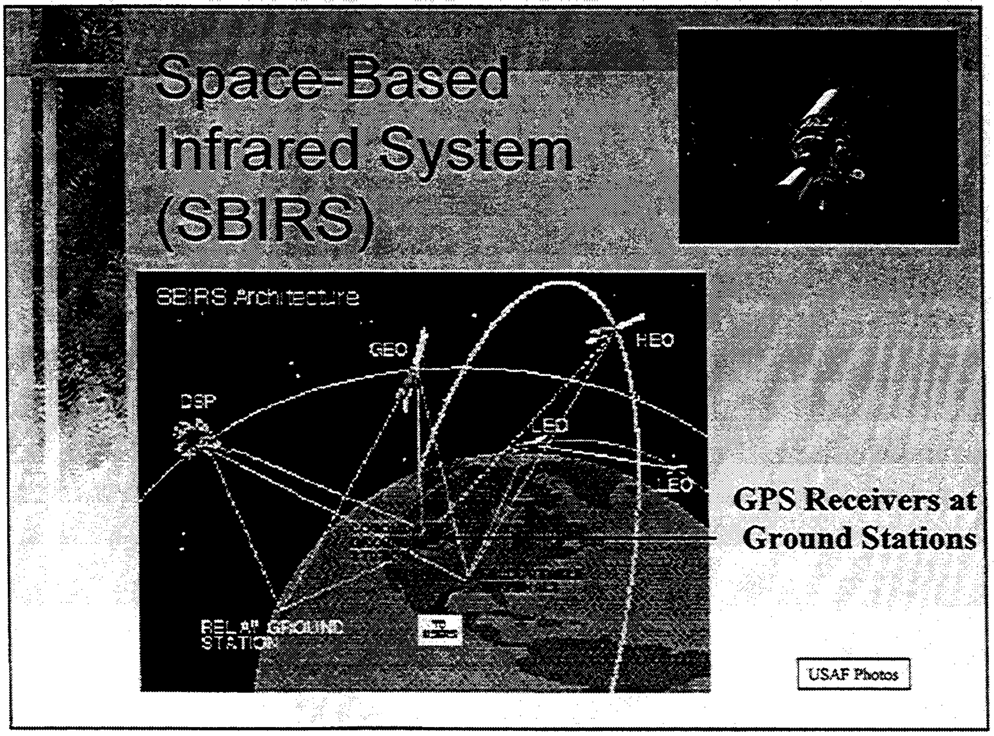

Figure 4. Space-Based Infrared Warning System (SBIRS)

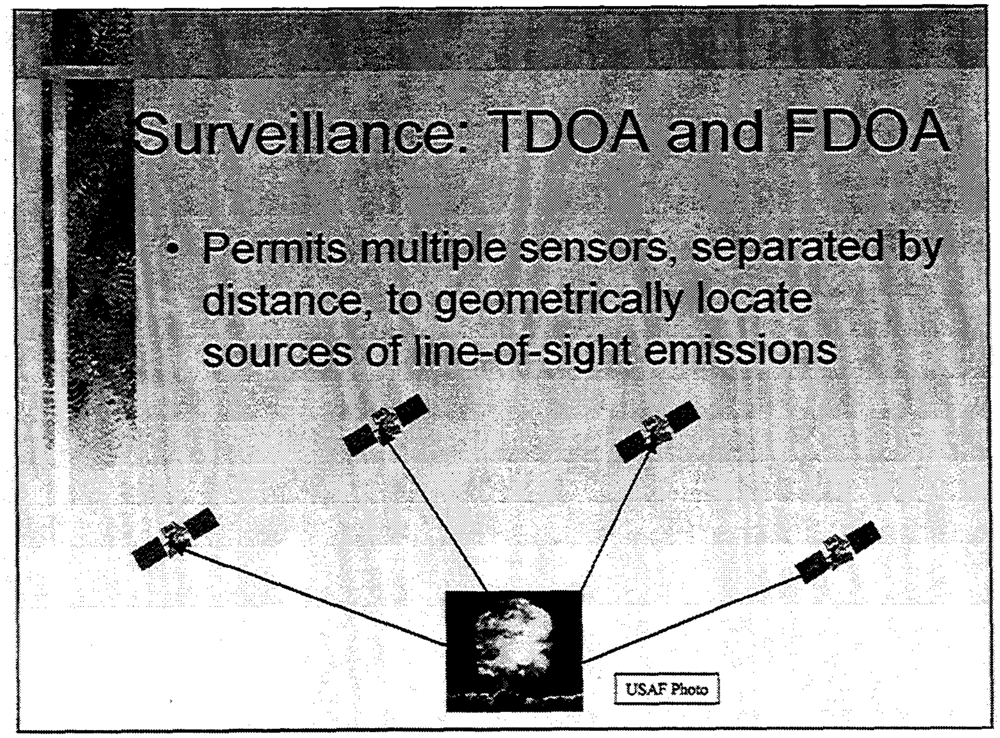

Figure 5. TDOA and FDOA

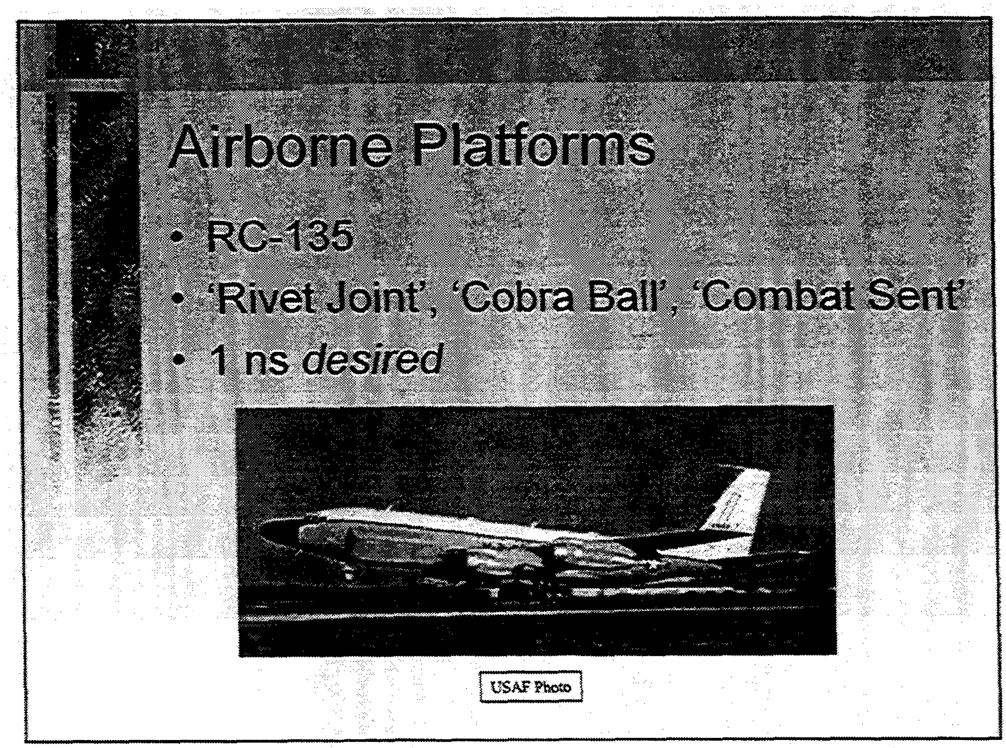

Figure 6. Airborne TDOA Users

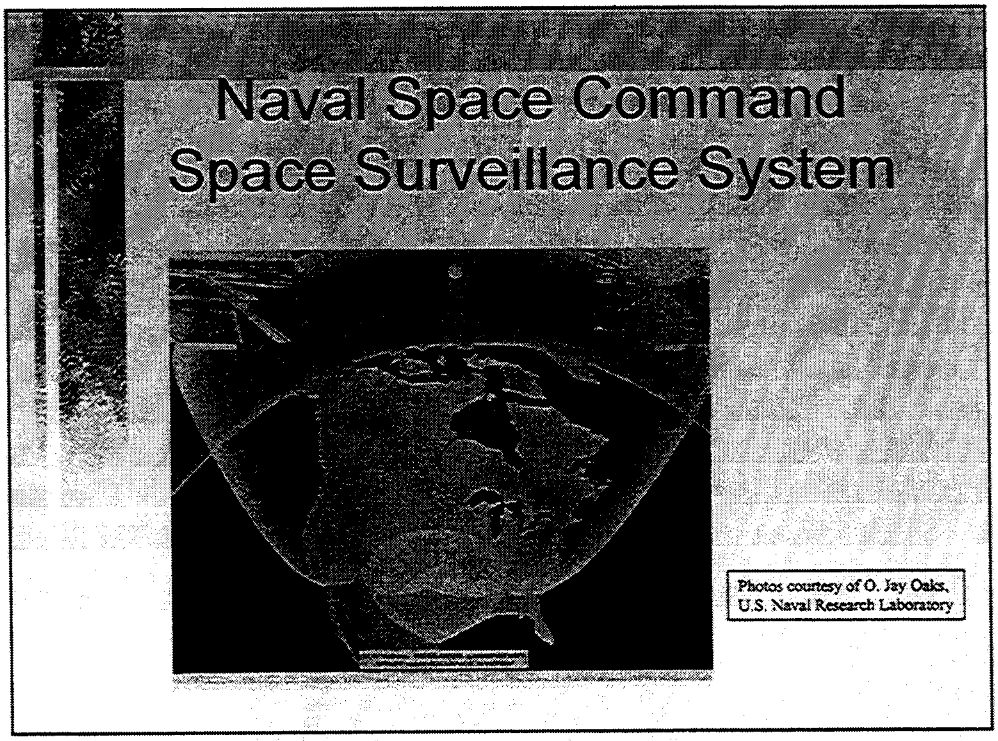

Figure 7. Naval Space Command Surveillance Fence

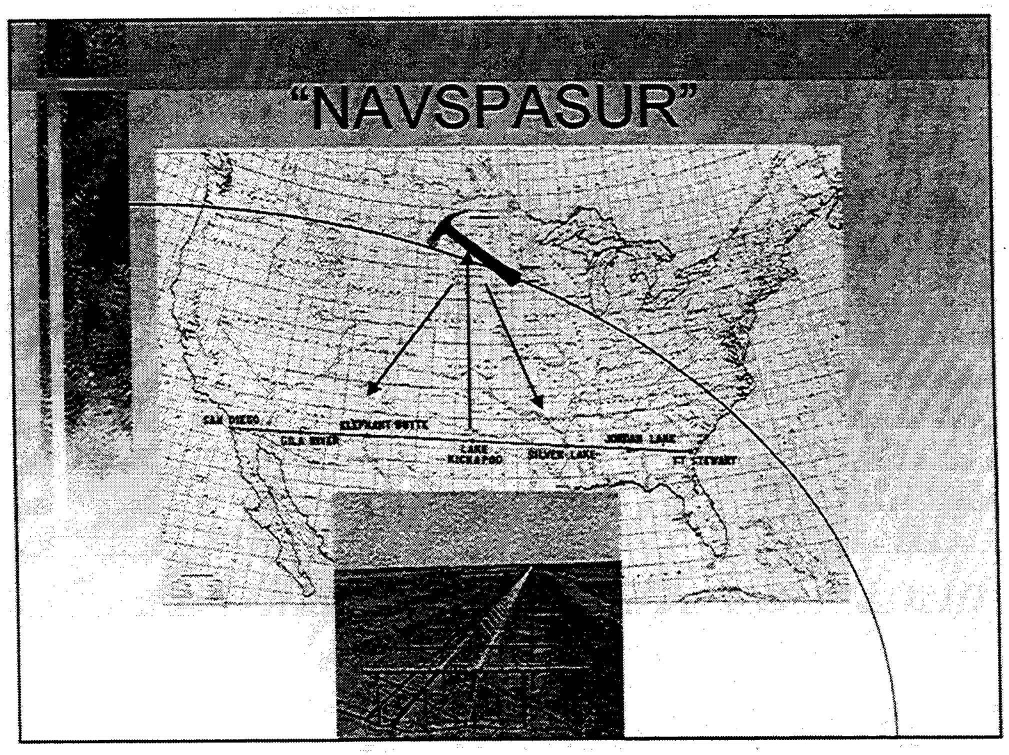

Figure 8. Geometric Space Surveillance Observations via "NAVSPASUR"

Questions and Answers

CAPTAIN D. C. CONROY (USAF): Are you saying that you believe we need another ICD for the timing user or an appendix to ICD 200/201? And if so, who's responsible for generating that type of a document?

STEVEN HUTSELL (USNO AMC): I'm not suggesting an ICD. I think ICD 200 covers the interface between the Space Segment and the user. Obviously if there's interface between the JPO and the users, it's hard to define that with an ICD, because an ICD is kind of restrictive and so forth. I think the general heart of my answer to that question would be that the communication between positioning users and the JPO is a lot better, it seems like, than timing users. Because what we often see is an organization where the commander will say here's so many $K: make timing possible; and the organizations make it happen. And the lieutenant or the captain will do it. And as that goes on, they think they have something that works, but at the same time they have disconnected themselves from the JPO, and they may have not bought the best equipment for their purposes, because they're not precisely educated on all the idiosyncrasies of GPS, health issues, and so forth.

CONROY: Well, I guess I'd lobby back and ask if the timing requirements were accurately understood by the appropriate JPO organizations.

HUTSELL: Do you mean like form factors for equipment?

CONROY: Well, you're aware that during the Y2K testing this year we had a lot of users call into 2SOPS and say these are the problems we're having with our user equipment, and JPO didn't necessarily have anything to do with some of that user equipment. But where were those requirements documented that those users had so that the community understands them?

HUTSELL: A lot of them will be user-specific, because the one thing that the ICD doesn't do is tell you how you will use GPS for your system; GPS has way too many applications. And an ICD saying anything beyond what's available would be too restrictive. So it's up to the individual user to make sure they're making a smart use of it. For some applications, the JPO may not have the experience to help them with that, but in a lot of them they do. And a lot of users are simply not taking advantage of that expertise. It's one of those circular communications where because people are not communicating one way, it's not coming back the other way, and it's not being continuous as the years have gone by.