

Utilization of the Global Positioning System (GPS) for Timing Systems Under Range Standardization & Automation Phase-IIA Program

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Abstract

Lockheed Martin was awarded a contract at the end of 1995 by the US Air Force to upgrade the space lift range infrastructure at Cape Canaveral Air Force Station in Florida and Vandenberg Air Force Base in California. The goal of the RSA Program is to reduce the total cost per launch while meeting the Range safety requirements. This will be accomplished on both coasts by adopting industry standards and replacing antiquated instruments with Commercial-off-the-Shelf (COTS) equipment. Furthermore, common operation and maintenance procedures will be developed for both ranges in order to reduce the total life cycle cost and subsequent operation and maintenance expenses at both ranges. The purpose of this paper is to present the overall system requirements and system architecture for the three timing product subsystems.

INTRODUCTION

Our Timing System consists of three product subsystems: GPS Timing, Range Countdown, and generation of Time of Vehicle First Motion (TVFM). These three product subsystems will directly or indirectly utilize the precise timing information broadcasted by the GPS satellites to generate accurate time, stable reference frequencies, countdown clock, and first motion time to support launch and launch related activities in both ranges.

GPS Timing Subsystem

Lockheed Martin proposed a GPS-based timing system to provide accurate time-of-day information, precise & stable reference frequencies, and clocks to synchronize communication network, computer workstations, and radar & telemetry instruments. The decision of implementing a GPS-based timing system is based on three significant factors. (1) The GPS Timing System has a significant lower initial procurement cost and subsequent operation and maintenance expenses compared against a primary

timing source, (2) The timing information broadcasted by the GPS satellites is available on a 24-hour basis, and (3) the accuracy of the GPS time is directly traceable to the DoD Master Clock (UTC-USNO) located at the U.S. Naval Observatory.

Requirements

Currently the stringent requirements imposed upon the GPS Timing Subsystem are that each timing station must have an accuracy within +/- one microsecond of UTC-USNO, the station-to-station accuracy must also be within +/- one microsecond, and all of the time codes generated by the GPS timing receivers must conform to Inter Range Instrumentation Group (IRIG) Standard 200-95, "IRIG Serial Time Code Formats". The accuracy and stability of timing product data are based on one sigma confidence level (68%).

The subsequent derived requirement requires that each timing station must be within +/- 500 nanoseconds of UTC-USNO, and the reference frequencies generated by each timing station shall be maintained at a Stratum Two level stability (1.6×10^{-8}). Based on a recent survey of commercial market, a typical Standard Positioning Service (SPS) GPS timing receiver will meet all of the timing requirements by maintaining an average of +/- 150 nanoseconds accuracy with respect to the DoD Master Clock. Furthermore, the reference frequencies generated by the GPS receivers will maintain a long-term Stratum One level (1×10^{-11}) of precision and stability. It has been determined that SPS receivers will meet and satisfy all of the requirements imposed by the Air Force.

Implementation

Each GPS timing station will either be a single receiver station or a redundant station. The GPS timing stations will be located throughout each range, including remote instrumentation sites. Refer to Figure 1, RSA-IIA GPS Timing System Overview.

Single Receiver Station

Each single GPS timing station will consist of a GPS-synchronized time and frequency receiver in a 3.5 inch chassis plus an antenna and pre-amplifier. Each timing receiver will have a basic IRIG-B and a One Pulse Per Second (1pps) output. In addition to the two basic outputs, each single station will have outputs for 1, 5, and 10 MHz reference frequencies and a multiple time code output module. The single receiver station will be strategically implemented throughout each range to allow timing users to receive time codes and reference frequencies from the nearest GPS timing station.

Redundant Receivers Station

Each redundant GPS timing station will consist of a redundant GPS synchronized time and frequency receiver in a distributed amplifier chassis with a fault-sensing switch unit (FSSU) embedded in the chassis. One of the GPS receivers will be designated as the Primary and the other one designated as Secondary (backup). Both the Primary and the Secondary receivers will generate the same seven time codes and reference frequencies (1 PPS, IRIG-B, 1, 5, and 10 MHz reference frequencies, plus two optional outputs). The same outputs from both receivers will be fed into the FSSU. Each FSSU module

will receive and monitor the time codes or reference frequencies from both GPS receivers. In the event of an anomaly in the time code or frequency module in the primary GPS receiver, the FSSU will automatically detect the interrupt of time code or reference frequency and switch the output from the Primary GPS receiver to the Secondary GPS receiver. The redundant receivers stations will be implemented at all Consolidated Instrumentation Facilities (CIF), because the CIF provides a significant role in tracking the vehicle flight and ensures safety of the civilian community surrounding the range. The redundant system will provide enhanced reliability in support of the operation of CIF.

Concept of Operation

Initialization & Cold Start

Each GPS receiver is designed to operate on a 24-hour basis. In the initiation stage, the geodetic information of each GPS receiver location will be programmed into the GPS receiver. In the case where the geodetic information is not available or the receiver is being used as a mobile unit, the GPS receiver will be initialized in the "AUTO" mode to allow the receiver to perform the long-term position averaging after it is stationary. It should take approximately 10 minutes to have the receiver lock on to the GPS constellation and download the new almanac data prior to performing a timing solution. Once the GPS receiver has been initialized, it will receive the GPS almanac information and determine the health of each GPS satellite. This will allow the receiver to only track the satellites that are healthy based on the almanac information provided by the GPS.

Generation of Time Codes and Reference Frequencies

In order to allow the GPS receiver to achieve its optimal performance, the receiver will be allowed to track as many healthy satellites as possible. Multiple satellites offer the strength of averaging and minimizing errors. The effect of Selective Availability (S/A, intentional degrading of accuracy) can be reduced by increasing the number of satellites being tracked. The antenna of the GPS receiver will be placed where an unobstructed and full view of the sky is available. Once the receiver has been initially setup, it will track the satellites that are available over the horizon. The propagation delay induced between the antenna and receiver will be compensated for by programming the cable delay at a rate of one nanosecond per foot based on the length of the cable from the antenna to the GPS receiver. All of the COTS GPS receivers we have looked at have modular design and are capable of generating accurate time codes and precise reference frequencies by implementing a time code module or a reference frequency module in the timing receiver hardware chassis.

Monitoring Health and Status of GPS Timing Receiver

This section describes some of the features in the GPS receiver that can be monitored by a Network Manager via the RS-232 interface of the GPS timing receiver. The following bullets describe the capabilities in some of the COTS GPS receivers that are currently available:

- **Acquire and Lock onto the GPS Satellites:** The GPS receiver will provide an indication whether the receiver has locked onto the GPS constellation.
- **Time Quality Check:** In a case of an anomaly in the GPS constellation or defective antenna, the GPS receiver will be unable to track the satellites. When an anomaly occurs, the internal oscillator will drive the time codes and reference frequency outputs. Since the oscillator is not perfect, each GPS receiver will have an average oscillator error rate programmed and will calculate the error that is being induced by the oscillator. There are different levels of error indication that can be obtained based on the rate of drift of the internal oscillator. Each level can be set up to provide an alarm and report the status to the Network Manager.
- **Satellite List:** A Network Manager will be able to retrieve information from the receiver via the RS-232 interface to see which satellite is currently being tracked.
- **Alarm Notification:** Health and status of the receiver will be provided to the Network Manager via the RS-232 interface. In case of an anomaly, an alarm notification will be generated for the Network Manager to initiate repair or maintenance action.

Reliability, Maintainability, and Availability (RMA) of GPS Timing Receiver

Based on the performance values supplied by some COTS GPS receiver manufacturers, a typical GPS receiver will have a Mean Time Between Failure (MTBF) of 78,000 hours, and Mean Time To Restore (MTTR) of 1 hour.

Distribution of Time Codes and Reference Frequencies

Since the proposed Timing System has a distributed architecture, instead of a centralized system, it is the intent that time codes and reference frequencies from each GPS timing station will only be distributed to local users. Conversely, each user shall obtain time codes and reference frequencies from the nearest GPS timing station. In order to maintain the required accuracy and precision of time codes and reference frequencies, time codes and reference frequencies will be transmitted using dedicated copper or coaxial cables. The error induced in the cable delay will be compensated for by the individual user.

Test & Evaluation

Accuracy of the GPS Timing Receiver

Each GPS timing receiver will be factory-certified and tested to guarantee its accuracy and confidence level. It is intended that the accuracy of each receiver will be re-evaluated during a scheduled or unscheduled maintenance by measuring the 1pps output against another 1pps generated by a primary time source or from another GPS receiver that has been calibrated by a standard laboratory.

The Stability of the Reference Frequency

The reference frequencies, generated by the GPS timing receiver, will be measured against a calibrated frequency counter or reference oscillator. The reference oscillator must be either a primary standard, if available, or another GPS disciplined frequency standard at least of equal stability to the unit under test. The stability of the reference frequency will be measured by an oscilloscope. All clocks and reference frequencies will be verified to ensure that the stability is maintained at a Stratum Two level (1.6×10^{-8}).

Maintenance Concept

All of the GPS timing receivers and associated equipment will have modular design using solid-state electronic components. All of the repair and scheduled and unscheduled maintenance will follow the prescribed maintenance procedures mandated by the manufacturer.

Summary of GPS Timing System

The overall system architecture is defined based on the requirements specified in the Space Lift Range System (SLRS) Specification. The goal of a modernized GPS-based timing system is to reduce the cost of operation and maintenance. We believe the employment of a GPS-based timing system will enable both ranges to achieve this goal.

Range Countdown Subsystem

The Countdown Subsystem provides a timeline for coordinating a multitude of tests and system validations between the Range and space vehicle operator in preparation for the launch of space vehicles. This is to ensure that the range and vehicle operator are operating on the same time scale with a common lift-off time.

Countdown System Requirements

The current requirements, specified in the Space Lift Range System Specification, indicate that the Countdown Subsystem shall provide eight simultaneous countdown signals. The accuracy of the countdown signal shall be within +/- 100 milliseconds against the DoD Master Clock with a reference to a countdown script. The countdown format shall conform to the Inter Range Instrumentation Group (IRIG) 215-96 Standard. The Countdown Subsystem shall also provide the capability to allow authorized personnel to initiate, synchronize, suspend, resume, and terminate the countdown operation.

SLRS Countdown System Architecture Overview

This section describes the overall Countdown System Architecture. This includes how the countdown and lift-off signal will be generated and distributed to the Control and Display Segment (CDSEG), Instrumentation Segment (ISEG), and other internal and external SLRS users.

Countdown Data Format & Generation of Countdown Signal

There are four formats assigned under the IRIG 215-96: CS-511z, CS-522z, CS-513z, and CS-524z. There are two major determining factors why CS-524z was chosen. The first reason is that CS-524z allows the transport and display of countdown, vehicle first motion time, and lift-off indication as one data stream. The second factor is that the ASCII countdown data can be easily distributed using ATM/SONET transport medium. This is compatible with the proposed digital transport network that will be implemented under the RSA Program.

The CS-524z format consists of two elements. The first element is the countdown data, which consists of countdown information in days, hours, minutes, seconds, and tenth of seconds. The second element consists of the predicted or the actual lift-off time in days, hours, minutes, seconds, and milliseconds, and the launch information word. The launch information word provides the status of the launch vehicle. While the launch vehicle is still on the ground, the launch information word is represented with an ASCII "P" (predicted), which indicates that the launch vehicle is still on the launch pad, and the second element of the countdown data currently represents the predicted launch time. When the lift-off signal is received from the launch pad, the launch information word changes from an ASCII "P" to an ASCII "A" (actual), which indicates that the launch vehicle has lifted off from the launch pad and the second element of the countdown data represents the actual lift-off time.

The CS-524z countdown signal will be generated by a COTS countdown generator. The CS-524z will be outputted in an asynchronous ASCII format. It is intended to be transmitted at 9.6kbps with an RS-232 interface/connector. A total of eight (8) countdown generators will be procured to support the requirement of providing 8 simultaneous count signals. Each countdown generator will utilize an external IRIG time code with +/- 5 microseconds accuracy, generated by a GPS timing receiver, as the reference. The microprocessor, within the countdown generator, will be synchronized to the external IRIG time code and will generate the ASCII countdown data within +/- 100 milliseconds accuracy.

Distributing Countdown Signal to Control and Display Segment (CDSEG)

CDSEG provides a Local Area Network (LAN) connecting computer workstations to display operation data generated by various radar, telemetry, and optic instruments. The countdown data will be provided to the LAN server with an RS-232 physical connector and subsequently distributed to workstations via Distributed Computer System (DCS). Furthermore, an IRIG-B signal will be provided to the Network Timing Server (NTS) to allow all of the workstations on the LAN be synchronized to the same time.

Distributing Countdown Data to Instrumentation Segment (ISEG)

The ISEG provides tracking of vehicle flight utilizing telemetry receiving instrument, radars, and long-range and short-range optics instruments. The countdown signal will be distributed to these instruments via the Asynchronous Transfer Mode (ATM) network, digital microwave transmission system, or Synchronous Optical Network (SONET). The data format of countdown information will remain in ASCII throughout.

Distributing Countdown Data to External Range Users

The countdown data will be distributed to external Range users in the original ASCII format via the SONET/ATM transport medium. If the external user is located beyond the boundary of the Range campus, the countdown data will be delivered to a designated demarcation point. Subsequently, the data will be transported via another transport medium or carrier to the final user destination.

Concept of Operation

There are five functional capabilities that are required for the countdown subsystem, as specified in the Space Lift Range System Specification. These capabilities are: initiate, synchronize, suspend, resume, and terminate. All of these functional capabilities will be provided either via the keypad on the front panel or by an RS-232 interface from the countdown generator. Each functional capability is described below:

- **Initiate:** The countdown generator will be initiated by an authorized Range Operation personnel in order to perform the operation. Based on the operator input, the countdown generator could be programmed so the countdown can commence at a pre-determined time (UTC-USNO).
- **Synchronize:** The countdown generator could be adjusted to forward or retard the negative count based on the countdown script. An optional RS-232 interface will be available to receive the countdown clock generated by the vehicle user to allow Range operator to synchronize the range countdown to the user-generated countdown clock.
- **Suspend:** The countdown generator will provide the capability to allow authorized Range operator or Range user to suspend the countdown. The authorized personnel will be provided with the capability to suspend the count at a pre-determined time or instantaneously via an external interface to the countdown generator.
- **Resume:** The countdown generator will provide the capability to allow the authorized Range operator to resume the count from the termination of count suspend. The countdown generator will provide the capability to resume the count at a pre-determined time. This will allow the continuation of count for the operation.

- **Terminate:** The countdown generator will provide the capability to the authorized Range personnel to terminate the count upon completion of the operation.

Summary of Range Countdown System

The overall Countdown Subsystem architecture is entirely based on the requirements specified by the requirements stated in the Space Lift Range System Specification. The overall architecture will standardize the operational procedures and provide reduced cost of maintaining different hardware at both ranges. Furthermore, the new Countdown Subsystem will incorporate the features to integrate TVFM Subsystem in a common hardware chassis to enhance operation capability at both ranges.

Time of Vehicle First Motion (TVFM) Subsystem

The TVFM Subsystem generates the time and lift-off indication associated with the occurrence of the lift-off event. The first motion is primarily used as an event marker for the start of vehicle flight. The telemetry and metric-processing computers use the lift-off indication and time of first motion to compute the real-time position of the launch vehicle against the trajectory data to ensure the vehicle flight is nominal.

TVFM System Requirements

There are two requirements that are imposed upon the TVFM system. The first requirement is to time tag the lift-off event within +/- 10 microseconds after the lift-off signal is received. The second requirement is to distribute the TVFM and lift-off indication to internal and external Range users.

TVFM Subsystem Architecture Overview

Generation of TVFM

Since CS-524z countdown format has the provision of including the TVFM as part of the data stream, it is the intention to build the TVFM Subsystem as an integral part of the Countdown System. The vehicle user will be required to provide a 1 KHz sinewave to the range in order to generate the TVFM. While the launch vehicle is on the ground, a 1KHz sinewave is generated and distributed to the Range. Once the launch vehicle is lifted off from the launch pad, the 1 KHz sinewave is interrupted. The 1KHz sinewave will be transported, via a DS-0 voice channel off the SONET transport medium, to the countdown generator. When the countdown generator detects the interrupt of the 1KHz sinewave for a minimum of six milliseconds, the TVFM is generated. The generation of TVFM will take into consideration and compensate for the six milliseconds delay and the delay of distributing the 1KHz sinewave through the SONET transport system to ensure the TVFM data is accurate. (Refer to Figure 2, TVFM Subsystem Overview)

TVFM Hardware

Since the TVFM will be an integral part of the Countdown System, the TVFM subsystem will share the countdown generator hardware chassis with an implemented Event Capture Module. Once the TVFM is

generated, the time of vehicle first motion information will be provided to the Countdown Subsystem and the TVFM information (lift-off time and indication) will be included as part of the countdown data stream. The receipt of lift-off signal will also trigger the launch information word from an ASCII "P" to "A" which indicates that the lift-off event has occurred.

Transport of TVFM & Lift-Off Indication

The TVFM and lift-off indication will be distributed to CDSEG, ISEG, and other users as part of the countdown data stream. The TVFM and lift-off indication will be transported in the same manner as the countdown information.

Test of TVFM System

The TVFM will be verified against the IRIG time code generated by a GPS timing receiver. The accuracy of the TVFM is based on the receipt of the lift-off signal by the event capture module excluding the transmission delay. Since the TVFM is referenced to the IRIG time code input into the countdown generator, the accuracy of the TVFM will be that of the accuracy as the input reference IRIG time code.

Issue & Concern

The only issue that remains with the TVFM Subsystem is the requirement to time-tag the lift-off signal to within +/- 10 microseconds after the lift-off signal is received in the range. The concern is the delay variation of sending the lift-off signal through the SONET multiplexers and transport equipment, which may exceed 10 microseconds. This issue is currently being looked into to determine if the delay through the ATM or SONET can be minimized to within 10 microseconds.

Summary of TVFM System

The TVFM System will be an integral part of the Countdown Subsystem sharing the common hardware chassis. An integrated Countdown and TVFM System will relieve the Ranges from customized hardware and software systems and allow the government to realize subsequent savings in the areas of operation and maintenance.

Summary

The goal of the RSA program is to utilize COTS equipment with a standard management interface for ease of control, configuration, and management. The GPS Timing System, Countdown Subsystem, and Time of Vehicle First Motion Subsystem will utilize COTS equipment with the anticipation that subsequent operation and maintenance expenses can be minimized. The GPS Timing System and associated subsystems will be implemented beginning in August, 1998. Test and evaluation data from these subsystems will be collected to verify the requirements and performance imposed by the customer.

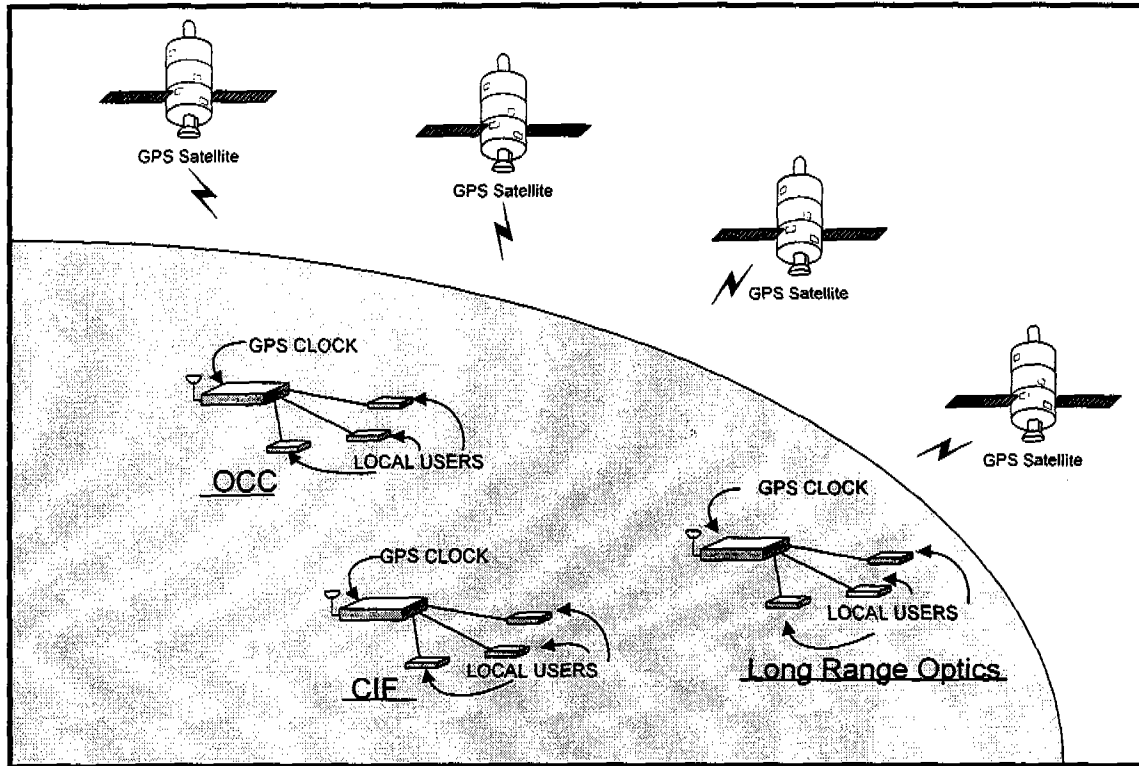


Figure 1 RSA-IIA GPS Timing System Overview

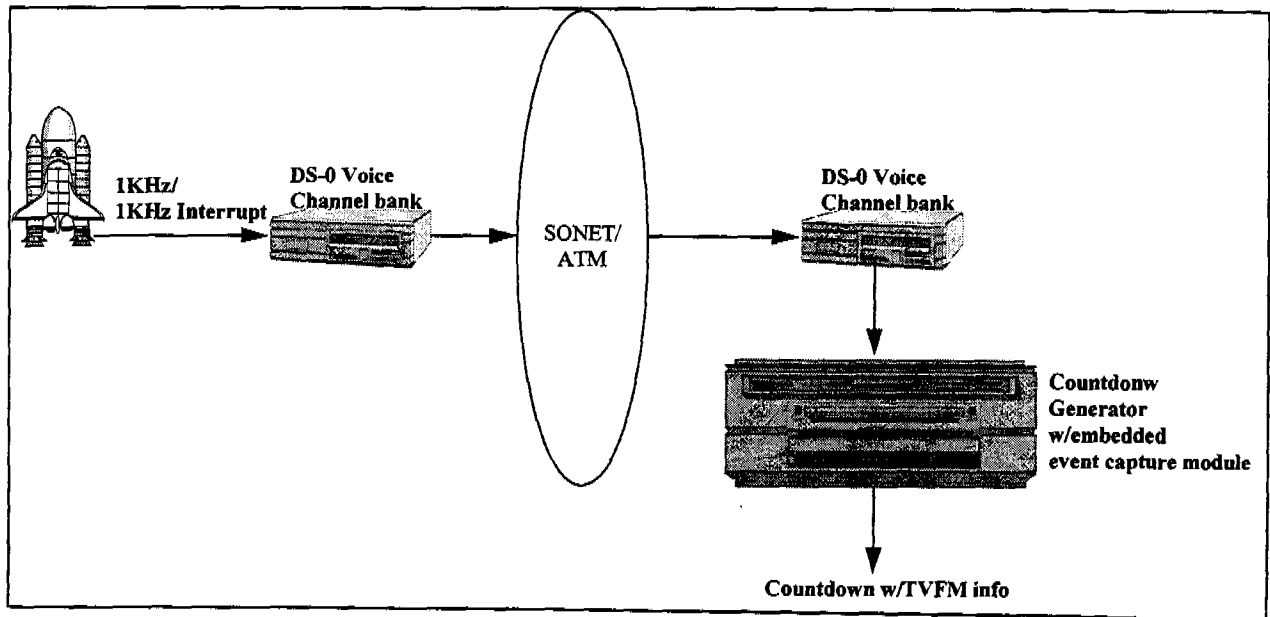


Figure 2 TVFM Subsystem Overview

Questions and Answers

JEFF INGOLD (ALLIED SIGNAL TECHNICAL SERVICES): Just wondering, you mentioned that you have not designed this yet. On the GPS segment, you said it was going to be CA Code. Have you picked if it is going to be a GPS-disciplined quartz oscillator or a rubidium?

MING LEE (LOCKHEED MARTIN): It is going to be a quartz oscillator.

HAROLD CHADSEY (USNO): We are currently controlling a cesium clock there via a micro-stepper. We are also doing the same thing at Vandenburg. Is this going to be an enhancement to that system and alternate to it, or how is it planned to be implemented?

MING LEE: I think my program will be totally separate from what is being done with a micro-stepper. I am not familiar with that part of the timing system in the Eastern range. As far as on the Western range, I believe that the company you are talking about is Precision Measurement Electronic Labs, so that is not part of the range. I do not think I will be dealing with that aspect of it. I am strictly dealing with the operation of the range.