Precise Timing Applications at the Defense Mapping Agency

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Abstract

The mission of the Defense Mapping Agency (DMA) focuses on satisfying the Mapping, Charting and Geodesy (MC&G) requirements of the U.S. Department of Defense (DoD). DMA satisfies these requirements by supplying a broad spectrum of products and services to its DoD customers. In many cases, DMA's products and services are also available to civilian and international organizations. Within this myriad of products and services, two DMA processes employ atomic frequency standards. Both of these operational processes fall in the discipline of geodesy.

DMA's geodetic exploitation of the Navstar Global Positioning System (GPS) is one area which requires precise timing. Since 1989, DMA has generated precise ephemerides and clock state estimates for the GPS satellites. This process depends on the performance of atomic oscillators in place at five DMA and five Air Force GPS monitor stations. This geodetic application also requires routine knowledge of the difference between Coordinated Universal Time (UTC) and the Earth's rotation rate (UT1). Another DMA process which relies on precise timing falls under the discipline of gravimetric geodesy. In addition to the routine collection of conventional (relative) gravity observations, DMA also collects measurements of absolute gravity at discrete points on the Earth's land surface. These absolute gravity observations are collected with a specialized instrument (an absolute gravity meter) which measures the speed of a falling object. This instrument employs an integrated rubidium frequency standard which is used in the measurement process. These DMA applications of precise timing are reviewed and discussed.

INTRODUCTION

Beginning in the 1970s, before the dawn of the Navstar Global Positioning System (GPS), DMA employed precise timing devices at a globally–distributed network of Doppler tracking stations. This network, when terminated in September 1993, consisted of approximately 40 stations. These tracking stations used either the MX 1502 DS receiver or the TRANET II receiver. In this network application, both receiver types employed rubidium frequency standards as a precise timing source. The satellites tracked by these stations emitted the well–known 150/400 MHz 'Beacon' signals. The Navy's TRANSIT and GEOSAT satellites are probably the most widely–known examples of DoD missions which relied on the DMA Doppler tracking network. Perhaps one of the largest collections of atomic oscillators managed by one organization, the frequency standards associated with the DMA Doppler network have now been dispersed to other applications within the DoD. Some of these frequency standards now serve as backup units to the DMA GPS monitor stations.

Currently, DMA uses precise timing devices in the geodetic exploitation of GPS and in a gravimetric geodesy application. These applications are discussed below.

PRECISE GPS ORBIT DETERMINATION

As most GPS users know, the entire GPS concept is based on our ability to precisely measure time and time interval. A common phrase used to describe the GPS concept to new users of this technology is 'clocks in space'. While these on-board cesium and rubidium frequency standards have been studied and described elsewhere, the clocks on the ground at the DoD GPS monitor stations are also an important component of the GPS constellation and will be discussed in some detail here. The global distribution of Air Force and DMA tracking stations is shown in Figure 1. The 'smoothed' pseudorange data collected by these stations are used in the DMA orbit process to estimate orbit, clock, and other parameters on a routine basis. Unlike the estimation process used at the GPS Operational Control Segment (GPSOCS), the DMA orbit/clock estimation process requires the designation of a 'master clock'. The offset and drift (phase and frequency) of this master with respect to 'GPS time' is held fixed during the estimation process. Because the designated master clock is not synchronized and syntonized with GPS time, all clock estimates generated in the DMA process are subsequently adjusted into coincidence with respect to GPS time through an empirical procedure which computes and applies the mean difference between DMA satellite clock estimates and the GPSOCS satellite clock estimates which are referenced to the GPS 'composite clock'. A detailed description of the GPS composite clock is given in Brown [1991].

To provide additional geographic coverage and to eliminate the complication of choosing a master clock for each weekly processing span, a sixth DMA station is being installed at the US Naval Observatory (USNO), located in Washington D.C. This DMA/USNO station will consist of hardware which is identical to other DMA stations (Figure 2) with one important exception. In place of the usual single cesium frequency standard, this station will employ the USNO atomic clock ensemble which supplies our national time standard: UTC (USNO). Beginning in mid-1995, the continuous stream of GPS tracking data collected by this station will be used in the DMA orbit/clock estimation process. Because of its extremely high reliability, the USNO clock ensemble will serve as the permanent master clock in the DMA process. The empirical adjustment procedure described above will remain in use because GPS time is not completely synchronized with UTC(USNO). If the adjustment procedure is not performed, the DMA satellite clock estimates would be expressed with respect to an extrapolation of UTC(USNO) based on a particular epoch, rather than GPS time. Of course, the magnitude of these adjustments is commensurate with the level of coincidence between UTC (USNO) and GPS time, currently on the order of 10 nanoseconds [NRL, 1995].

UT1-UTC

Any precise orbit determination process requires the application of a transformation from an Earth-Centered, Earth-Fixed (ECEF) reference frame (WGS 84 in DoD applications) to an Earth-Centered Inertial (ECI) Reference Frame (such as J2000). This transformation incorporates knowledge of the variations in the Earth's rotation rate and polar motion. The difference between UTC and the time scale based on the Earth's rotation (UT1) enters directly into the ECEF to ECI transformation. To satisfy this need for several DoD satellite applications, DMA generates weekly predictions of UT1–UTC and polar motion which are collectively referred to as Earth Orientation Prediction Parameters (EOPP). These DMA predictions are generated in conformance with an Interface Control Document (ICD–GPS–211) and are based on weekly 'Bulletin A' International Earth Rotation Service (IERS) rapid service information supplied by the USNO Earth Orientation Division.

While significant advancements in atomic frequency standards have occurred over the last few decades and GPS–time was designed to allow most users to avoid the complication of leap seconds, GPS and other practical orbit determination applications continue to employ these advancements in concert with precise knowledge of the Earth's rotation rate. The predictability of the UT1–UTC parameter will continue to play a key role in these practical DoD applications. Inevitably, all satellite tracking measurements must be tied to stations which reside on the rotating Earth.

ABSOLUTE GRAVITY MEASUREMENTS

The structure of Earth's gravitational field has been studied through the use of several technologies including traditional relative gravity meters, analysis of orbit perturbations observed through satellite tracking data, satellite altimetry data and the recently–developed transportable absolute gravity meter. The absolute gravity meters developed in the US measure the speed of a falling corner–cube reflector in an evacuated 'dropping chamber'. A detailed description of this instrument can be found in Carter et al, 1994. To obtain a gravity observation accuracy of a few microgals (1 microgal = $1 \times 10^{-8}\ ms^{-2}$) an accurate length standard and an accurate time standard are needed. The length standard is established by an iodine stabilized laser while the time standard is established by a rubidium frequency standard. To obtain the microgal–level gravity observations, the stability of the frequency standard used in this process needs to be on the order of 5 parts in 10^{10} (over a range of intervals) and the length standard needs to be accurate at a level of 1 part in 1010 (Niebauer, 1994). While the requirements on the frequency standard are not particularly demanding, practical considerations such as the size of the instrument and the amount of time needed to 'warm–up' limit the widespread use of these absolute gravity meters. Technological advancements which would reduce the size and warm–up time of atomic frequency standards would help to promote further miniaturization and portability of these devices.

SUMMARY

Two areas of DMA's geodetic mission require the application of atomic frequency standards. The first area revolves around precise GPS orbit and clock estimation. To assist this process, a sixth DMA GPS monitor station will be installed at the USNO in Washington D.C. in mid–1995. The USNO clock ensemble will serve as the time standard for this DMA 'master station'. Additionally, the USNO's Earth Orientation Division will continue to supply the basic observational data on the variation of the Earth's rotation and its polar motion.

The second area of DMA's mission which requires atomic frequency standards is the measurement of absolute gravity on the Earth's surface. The transportable absolute gravity meters developed in the U.S. require a frequency stability of 5 parts in 10^{10} over a range of intervals. This requirement is now met by an off–the–shelf rubidium standard. Advancements in the development of future, smaller, easily portable absolute gravity meters require that the frequency standard also becomes smaller and more portable. For this reason, further miniaturization of atomic frequency standards would directly benefit the development of smaller absolute gravity meters.

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DoD GPS Tracking Network

● Air Force Tracking Station ■ DMA Tracking Station

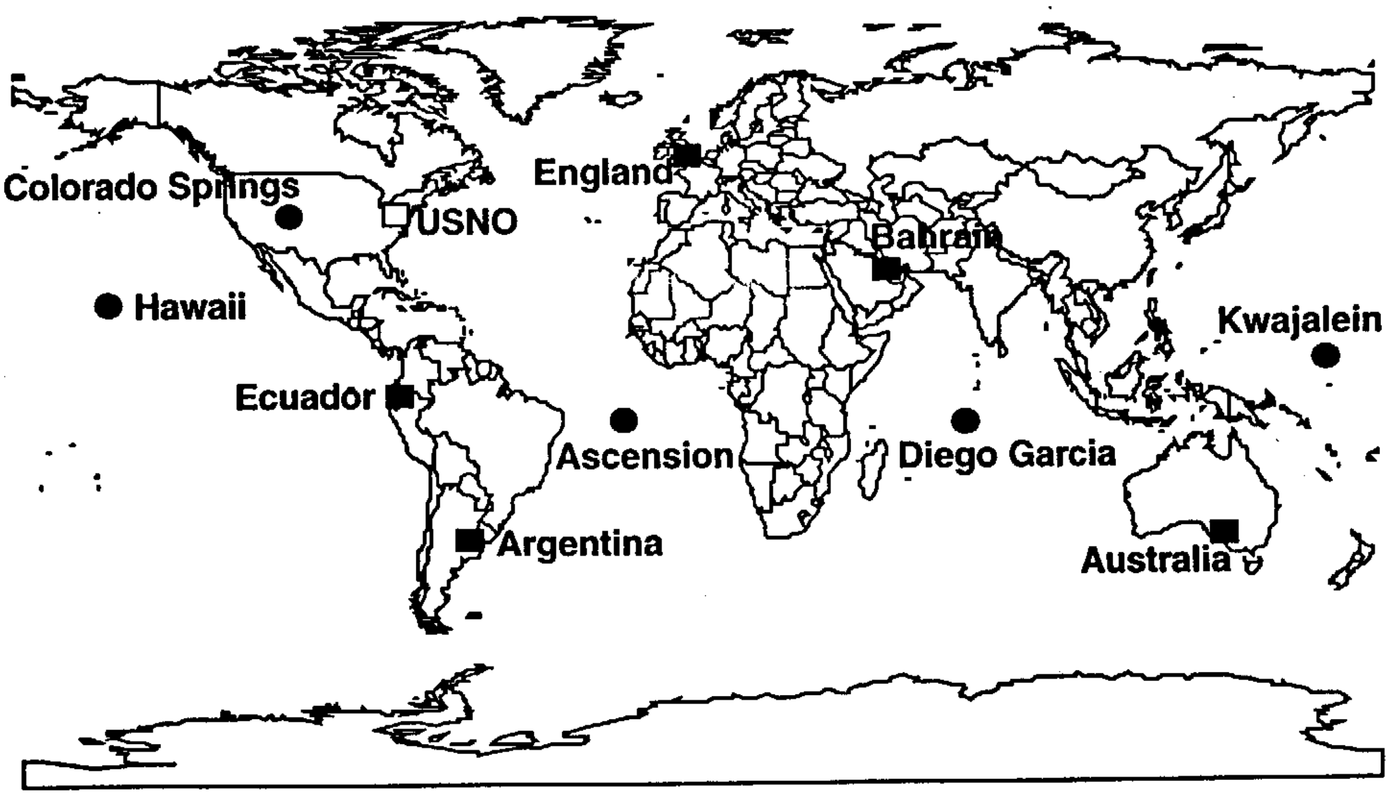

Figure 1

DMA GPS Monitor Station

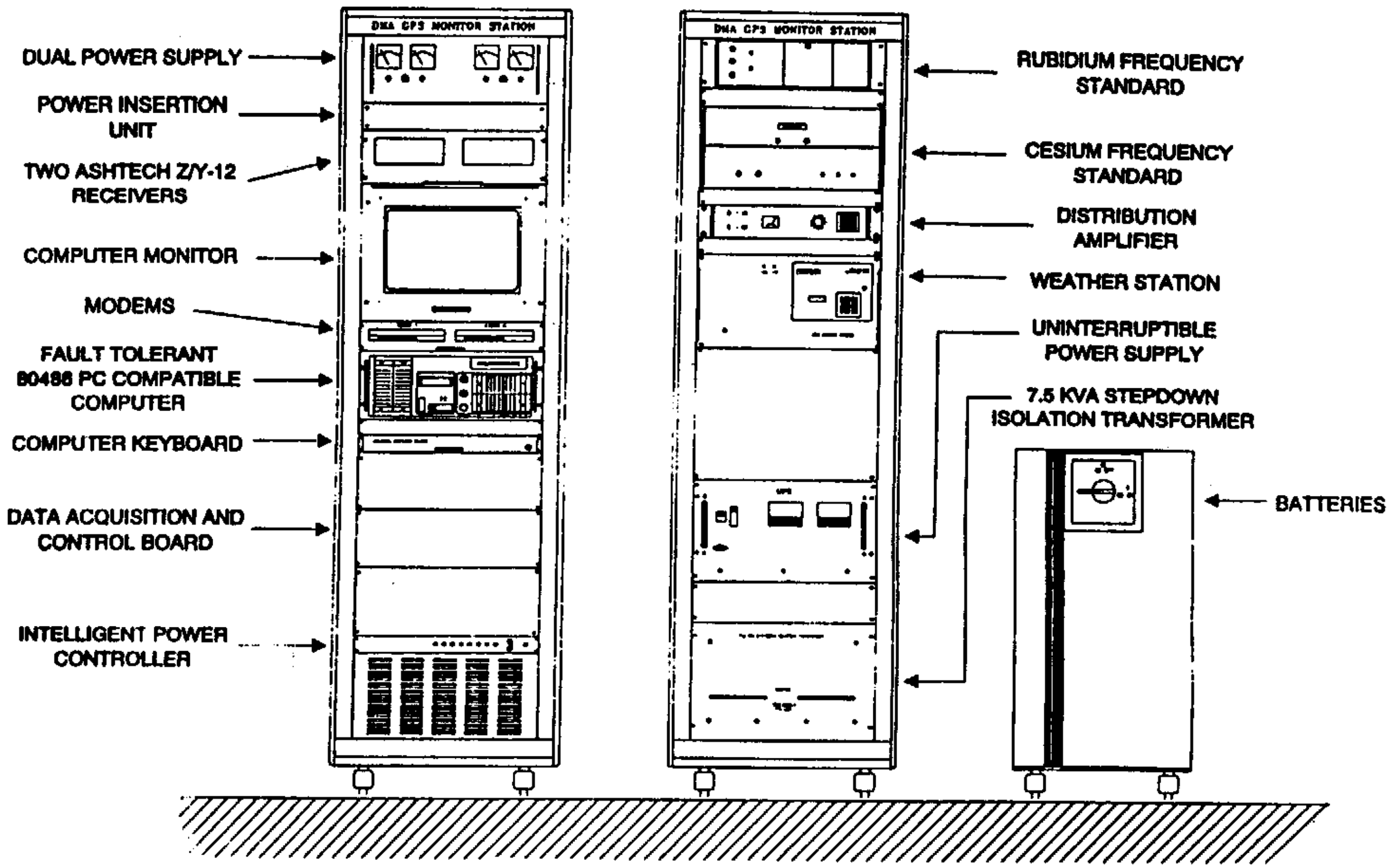

Figure 2

QUESTIONS AND ANSWERS

PETER WOLFF (BIPM): I have two questions. First, can you give an order of magnitude on your orbit accuracies and clock offset accuracies?

STEPHEN MALYS (DEFENSE MAPPING AGENCY): Yes. Together, if you think about the orbit accuracy in terms of range error when you use the DMA ephemeris and clock together, we get range errors on the order of a half a meter. That would be considered an RMS over a day or the general performance level.

If you're asking for a more specific breakdown of orbit error versus clock error, it's somewhat higher than half a meter. We see each component to run about one meter, but it varies by component.

PETER WOLF (BIPM): Okay. And secondly, the order that you use for your orbit determination, is it in the form of differences of data between two stations? Are you differencing the ranges or is it just the direct range measurements that you get by each station?

STEPHEN MALYS: It is the direct range measurement. We refer to it as a smooth pseudo-range. It's the same observable that's used in the master control station's orbit determination process, but it is strictly a range measurement.

PETER WOLF: And that's affected by SA in new data?

STEPHEN MALYS: Well we remove SA; we have a facility to remove it.

JUDAH LEVINE (NIST): The absolute gravity measurements have a first order correction to the barometric pressure of both local and regional. Could you say a little bit about how you do those kind of corrections?

STEPHEN MALYS: I didn't come prepared to answer that particular question. I know that the clock stability and, of course, the link standard are two of the primary things you have control over when you make the measurement. We certainly do take barometric pressure into consideration when we take those gravity observations.

When you're looking for the best possible precision, there are many things that you have to take account of, even things such as the amount of ground water that's present at the time that you take the observation. So it's get rather complicated when you're trying to squeeze out every single milligal.