

THE ROLE OF TIME AND FREQUENCY IN THE MTSAT SATELLITE-BASED AUGMENTATION SYSTEM (MSAS)

Toru Ishita, NEC Corporation, Tokyo, Japan

Aileen S. Nii, ISI Satellite Navigation Division, Inc., Vienna VA

Abstract

The MTSAT Satellite-based Augmentation System (MSAS) is a satellite-based augmentation system (SBAS) for navigation. The MSAS is one of several applications that shares the use of the Multifunctional Transport Satellite (MTSAT), a geostationary earth orbiting (GEO) satellite, which will be launched by the Japanese Ministry of Transport in August 1999. The MSAS design is based on the development of the US Wide Area Augmentation System (WAAS) and therefore may be familiar to those who are acquainted with the WAAS. Time and frequency play a critical role in four areas within MSAS, and these areas are the focus of this paper.

Firstly, MSAS performs several functions. One – it collects data from the NAVSTAR Global Positioning System (GPS); two – it provides an independent ranging signal from MTSAT to supplement the navigation signals from the GPS constellation; three - it provides differential corrections to improve the navigation capability of the GPS; four – it provides the offset of MSAS Network Time (MNT) from Coordinated Universal Time (UTC); and five – it provides system integrity information to the user. With these functions, the MSAS can become the primary means of time distribution and synchronization within Japan and other areas under the footprint of the MTSAT. The accuracy and precision attainable by MSAS is critically dependent on the performance of the time and frequency subsystems in the four areas of discussion.

The first area of discussion is the manner in which the data recording system tags its observations. Accurate recording of the time of observations is essential in order to measure the timeliness (latency) of all transmitted information. This information is based on algorithms that derive their input from data collected from a network of eight data collection sites, including four Ground Monitoring Stations (GMS) and four Monitor and Ranging Stations (MRS). Each GMS/MRS has three independent, free-running cesium-beam frequency standards.

The second is the discussion of the method of deriving the MNT and keeping it close to GPS Time. The MSAS, through the Master Control Stations (MCS), maintains MNT, its own local time scale, and is steered to a real-time estimate of GPS Time. Only an estimate of GPS Time can be made because GPS Time is affected by Selective Availability (SA). It is essential to have a uniform time scale as a reference in order to derive differential corrections that improve the

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accuracy that can be obtained from the GPS Standard Positioning Service (SPS).

The third topic of discussion is the manner in which the MSAS navigation message from the MTSAT is controlled and transmitted. The signals transmitted from the MTSAT, which can be used as a supplemental ranging source to GPS, must be emitted in synchronization with GPS signals in order to make them compatible within a common navigation solution.

The last area of discussion is the secondary mission of the MSAS. Like the WAAS [1], it is to provide UTC. It does this by comparing MNT, which is synchronized to GPS Time, with UTC, as maintained by a UTC provider. For the WAAS, it is the US Naval Observatory (USNO). Although the Japanese Civil Aviation Bureau (JCAB) has yet to make a decision to provide the time distribution service, the procedures for obtaining, calculating, and transmitting the offsets of MNT from UTC, as part of the MSAS navigation message, is described.

INTRODUCTION

In the past, history tells us that navigation systems have depended on time, and therefore timekeepers have looked to navigation systems for the distribution of time, accurately and timely. Today, the crux of the GPS relies upon a highly evolved clock technology. However, unlike navigators, who need four GPS satellites by which to navigate, timekeepers only need one GPS satellite to determine time if they know their position. The observations of only one satellite will also allow timekeepers to remotely synchronize clocks around the world.

The MSAS is one of the most recent developments in the evolution of navigation systems. While it is somewhat similar to other differential GPS systems in concept, the MSAS provides the JCAB and the air navigation community a significantly higher level of performance than the GPS SPS and other differential systems dependent upon GPS. Based on the augmentation methods utilized by the MSAS, it provides not only improved accuracy, but also increased availability, integrity, and continuity of service. It accomplishes this by continually monitoring GPS transmissions from the GMSs/MRSs and by transmitting an augmented message from the MTSAT 1 presently, and MTSAT 2 and other GEO satellites in the future. The signal from the MTSAT, while sharing the same frequency as the GPS L1 frequency, is different in format and bit rate.

THE MSAS PROCESS

The MSAS process is illustrated in the diagram of Figure 1. There are four GMSs distributed throughout Japan at the JCAB's Area Control Centers (ACC) in Sapporo, Tokyo, Fukuoka, and Naha (in Okinawa). Two MRSs are collocated at the MCSs at Kobe and Hitachi-Ohta, and two MRSs, in Australia and Hawaii, respectively. Each GMS and MRS consists of three independent subsystems or sets of ground monitoring equipment (GME). Each GME consists of a cesium-beam frequency standard, a 12-channel, dual frequency MSAS-GPS receiver and a wide and a narrow band GPS receiver that continually track all GPS satellites and GEO satellites available to them. The data obtained at these ground-monitoring stations (GMS/MRS) are transmitted to two MSAS master control stations (MCS) where the MSAS navigation messages and MSAS Network Time are formed. Each MCS consists of three major subsystems – the Central Processing Facility (CPF), the Navigation Earth Station (NES), and the Monitor

and Control (M&C). The navigation messages contain information on satellite orbits, the current state of the ionosphere, system health, and timing information. Each MCS passes the navigation message to two Ground Earth Stations (GES), where it is uplinked by one GES to the MTSAT 1, the Phase 1 GEO satellite, which then transmits it to the user. The MTSAT Tracking and Telemetry Control (TTC) facility is also collocated with the GES and MCS at the Aeronautical Satellite Control Center (ASC) sites in Kobe and Hitachi-Ohta. The ASC provides shelter, power, and operations and maintenance services for all systems located at the site.

Each GMS/MRS performs the functions of data collection, reasonability check, data processing, and data transfer. Each GMS/MRS consists of triple redundant GMEs that collect three, independent sets of data, including GPS satellite observables and GEO satellite observables, and transmits the data to the CPFs at both MCSs in the system. Independence of the data sets is ensured by gathering the observable parameters through independent sets of equipment that are necessary to support the verification function performed by the CPF at the MCS. Prior to transmitting data to the MCSs, each GME verifies the reasonability of its collected data. Failed data are marked as having failed the reasonability test and are then forwarded to the MCSs. To ensure the availability of the data at each MCS, each GMS/MRS transmits data to each MCS through two independent communications networks, known as the Network Communications System (NCS) in the MSAS.

At each MCS, the CPF performs the functions of corrections processing, satellite orbit determination, integrity determination, and the verification, validation, and the MSAS message generation. Once per second, the CPF collects the data received from all GMSs/MRSs and processes them to support the functions described above. This processing is performed on all available GME data and results in the transmission of a formatted, 250-bit, MSAS message once per second. These MSAS messages are sent to both NESs. The timing of MSAS processing is scheduled to allow broadcast of the resulting MSAS message from the MTSAT coincident with the following GPS 1-second Coarse/Acquisition (C/A) code epoch. The MSAS validates the Signal-in-Space (SIS) by checking the downlinked messages to ensure that they are identical to those transmitted to the MTSAT and by comparing navigation position solutions from MSAS and GPS with the surveyed GMS/MRS locations. From each M&C console, control over the MSAS can be exercised via a computer-human interface. To avoid conflicts, only one MCS and, therefore, only one M&C subsystem console attended by the Controlling Operator, can be designated as the controlling MCS at any one time within the MSAS.

The initial MSAS design for Phase 1 implementation has two MCS/GES/TTC combinations that perform the functions of broadcast and ranging. Each MCS has one CPF that formats the 250-bit MSAS message. In MSAS, there is the advantage of the MCS facility collocated with the GES/TTC facilities, and it is that that improves the availability of MSAS messages. Each NES, which includes the MSAS Signal Generator (MSG), selects one CPF as its message source and encodes the received message using a half rate forward error correcting (FEC) convolution code. The resulting 500-bit message is modulated on a GPS-type signal and uplinked to the MTSAT. Both GESs serve the MTSAT; one operates as the primary uplink, and the other operates as a hot standby. The two GESs serving the MTSAT are operationally independent and located at geographically diverse ASCs separated by a minimum of 300

miles. Each ASC facility currently services only one GES. When there are at least two GEO satellites, each GEO satellite will be served by two GESs, one from each ASC site. The MTSAT "bent pipe" transponder shifts the frequency of the signal and broadcasts it to the MSAS users. The transition between primary and backup GES is initiated, when necessary, to maintain the availability of the MSAS SIS.

The NES ranging function is accomplished by transmitting a signal to the users on the GPS L1 frequency with the following information: (1) a precisely timed Pseudo-Random Noise (PRN) code that is assigned to each GEO satellite and (2) a precise ephemeris that is contained in the GEO satellite navigation message, which is sent periodically in the broadcast function. This signal structure is achieved in a similar manner to that of GPS, except that the precise timing of the PRN code is carried out on the ground rather than on the GEO satellite or the MTSAT, in this instance. This function will allow the users to apply the MTSAT as another GPS satellite, thereby increasing overall system availability.

TIME AND THE GMS/MRS

The recording of the time of observations is an area of concern for the MSAS. All observations are made at the independent GMSs/MRSs. In order to ensure a uniform time basis at each GMS/MRS, a clock based on GPS Time is used as the reference.

Each GMS/MRS contains three GMEs that identify three identical threads. These threads are required for sufficient redundancy to provide data to the MCS in the event a single failure in the GMS/MRS occurs. In addition to other commercial-off-the-shelf (COTS) components contained in the GME, there is a cesium-beam frequency standard (Atomic Clock).

The frequency standard needs to meet certain specifications to be useful in the MSAS architecture. The functional requirements include:

- Accuracy
- Settability
- Stability
- Single Side Band Phase Noise
- Warm-up Time.

Accuracy shall be at least 2×10^{-12} with no aging for the life of the cesium tube, so that it can be tuned to a specified frequency. The frequency standard provides each MSAS receiver a 10 MHz sinusoidal wave reference signal with a stability of at least 2×10^{-13} over 24 hours in order to accurately compare the MTSAT signals with GPS Time. The GME frequency standards require communication via RS-232 interface to the data collection processor (DCP) for interrogation and parameter adjustments.

The 10 MHz output from the cesium-beam frequency standard is input to a GPS receiver that provides a 1 PPS output used as the epoch of observations. Figure 2 is a diagram of the role of the cesium-beam frequency standard in the GME at a GMS/MRS. **The receiver clock is set to GPS Time at start-up.** Thus, GME receivers are approximately synchronized to the level of several microseconds. **The output data stream of each MSAS monitor receiver contains a parameter that has the offset of the receiver 1 PPS from GPS Time.** After that the output 1 PPS is governed by the rate of the input cesium clock. In

essence, the output from the GPS receiver is a free-running clock. This is necessary for the formation of an independent time scale.

TIME AND THE CPF IN THE MCS

The CPF and M&C in the MCS embodies processing equipment necessary to perform the Corrections and Verification (C&V) and Monitor and Control (M&C) functions, respectively. There is also a GPS clock for synchronization with GPS and equipment to interface the MCS with the NCS communication circuits. There are two MCSs in the Phase 1 MSAS. The quantities are planned for increase in subsequent phase(s). The end-phase MSAS is projected to have up to at least four MCSs.

The CPF performs several functions. Those involving time, directly or indirectly, include:

- Determine GPS/GEO satellite orbits
- Monitor SIS performance
- Generate MNT
- Generate MNT/UTC offset message
- Generate MSAS messages.

The data from all three GMEs for each GMS/MRS are sent to each of two (for redundancy) corrections processors (CP) in the CPF subsystem and the data from each GME at a single GMS/MRS are compared. The clocks are monitored relative to each other to determine if one clock is "bad"; that is, it checks to see if it has a significant change in offset. The current Phase 1 design does not estimate the frequency offset between GME clocks. This is the start of the formation of the MNT, which is described in the next section.

MSAS NETWORK TIME

In order for the MSAS signal to supplement the GPS navigation signals, the MSAS transmissions must be synchronized to them, i.e., GPS Time. This is accomplished by establishing MSAS Network Time as the reference time for the MSAS. The MNT is steered to GPS Time. Measurements from all GMEs at all GMSs/MRSs are sent to each CPF at the MCSs, of which there are two in Phase 1. Each CP at each CPF has an MNT algorithm, and computes a potentially independent MNT time scale from the data received from the GMSs/MRSs. All "good primary clocks" involved in the GME measurements that a CPF CP receives are used to form the MNT time scale. This time scale is then steered to the GPS with the same algorithm.

At the CPF CP, the GPS satellite and GEO satellite orbits and clocks are calculated along with the input GME ground clocks relative to the MNT_i time scale (the localized MNT time scale of CP_i) [2]. The raw MNT_i time scale is an average of all the "good" input GME ground clocks. The output of the orbit determination program and clock filters is used to estimate the localized MNT_i -to-GPS offset. The difference between each GPS Space Vehicle (SV) clock solution and the broadcast ephemeris clock solution is an estimate of the MNT_i -to-GPS offset. Once per day, a linear fit to these offsets is calculated to determine MNT_i bias and frequency offset with respect to the GPS time scale. The MNT_i frequency is

steered once per day based on this estimate. The steering command is designed to drive the offset to zero. The steering filter (MSAS Phase 1 version) daily computes a linear-fit estimate between MNT and GPS. Step one compares the GPS clock solutions (given in MNT) with the broadcast ephemeris clocks that give estimates of the GPS clocks in the GPS time scale with SA corruption added. This difference is used as the input to the MNT to GPS estimation filter every 30 seconds.

Each CPF synchronizes its MNT_i of its master CP via a communications link to all other CPFs. At every pre-established time interval (Phase 1 interval is 5 minutes), the CPF exchange MNT_i via their estimate of all SV clocks. For each common SV clock estimate, the difference is a measurement of the bias offset between each MNT_i . Let MNT be the average of all MNT_i . Thus, at any time interval, MNT_i can be measured as the average of these SV clock differences. The MNT algorithm described above is implemented in each CP at the CPFs.

The MSAS messages include fast and slow corrections that are transmitted by the MTSAT. Fast corrections shall be determined for each GPS SV. This is accomplished by using the long-term correction message, which is broadcast from the MTSAT to remove the long-term clock offset in frequency from the extrapolated fast correction. Note that the total of the long-term and fast corrections must be added together before comparisons between the two CP outputs can be made.

It is estimated that the once-per-day steering may not be sufficient to keep MNT close to GPS Time. Therefore, the hardware steering will be supplemented by correction messages within the MSAS navigation messages. There will be slow correction messages and fast correction messages that are transmitted by the MTSAT. The slow correction will be updated once every five minutes and will take care of the major part of the correction. The fast correction will be issued every second and will compensate for the effects of SA. This steering filter described above has to be able to follow the GPS time scale because the GPS time scale is steered to UTC in a "bang-bang" method [3].

TIME AND THE MTSAT

The cesium clock at the NES will be slaved to the MNT. Once per day, the CPF will issue commands to steer the NES clock in order to reduce any offset from GPS Time. The NES clock controls the synchronization of the MSAS navigation message from the MTSAT.

The schematic relationship and the flow of data and time from the CPF through the NES (an MSAS subsystem), the GES, and the MTSAT at the ASC are illustrated in Figure 3. The MSG in the NES provides a C/A PRN code plus an MSAS message signal as a 70 MHz Intermediate Frequency (IF) to the upconverter. The IF is converted to the RF uplink frequency; then the GES amplifies it and transmits the signal to the MTSAT. The K-band uplink is received by the MTSAT and translated to the L1 and K-band downlinks, which are broadcast in right-hand circular polarization (RHCP) earth coverage beams to users and the GES. The GES receives the downlink L1 and K-band signals from the MTSAT. The signals are amplified and the K-band is converted to L2, and the L1 and L2 signals are provided to the NES.

The NES receiver accepts C/A PRN code signals at the L1 and L2 frequencies from the GES. The NES receiver measures code and carrier phase pseudorange data for both input signals. This information is sent to the NES processors and MSG, which have algorithms and hardware that develop time, frequency,

and phase feedback correction signals. The processor also FEC encodes the MSAS message. These correction signals adjust the time, frequency, and phase of the C/A PRN code signal to take out the uplink range, range rate, and ionospheric effects. The MSG also combines the FEC-encoded MSAS message data with this uplink-corrected C/A PRN code, which is provided as an IF signal to the upconverter in the NES. The frequency standard provides precise and stable frequency references for all the converters, signal generators, and receivers in the GES and NES. The frequency offset of the 5 and 10 MHz output shall be settable over a range of $\pm 1 \times 10^{-9}$. The Settability requirement is only applicable for the frequency standard at the NES, because this must be able to compensate for any drift in the MTSAT's local translation oscillator.

The GES transmits signals from the NES containing integrity and correction data along with a GPS-like ranging signal to the MTSAT. The NES receives signals from the MTSAT at both K-band, which is translated to L2 frequency, and L1 frequencies. The NES controls the uplink power levels to protect against uplink interference and variations in transmission losses. The NES provides frequency translation of the uplinked signal to K-band and translation of K-band downlink signal to L2 frequency.

The MTSAT subsystem is a satellite in geostationary orbit in space, at a longitude of 140 degrees East.

THE MSAS TIME DISTRIBUTION SYSTEM (M-TDS)

Like the WAAS, the MSAS has the capability to provide a time distribution service. Time distribution is accomplished by providing users with a time offset between MNT and UTC. This time offset is determined by the UTC provider and passed to the MSAS MCS through an interface between the MSAS and the UTC provider. Although the JCAB has yet to select the UTC provider, the description below provides the general approach and implementation of an M-TDS. The MCS collects the MNT/UTC offset and creates a Type 12 message, which is then sent to the GES, which transmits it to the MTSAT. The purpose of the Type 12 message is to provide time users with a more accurate source of time referenced to UTC. The UTC provider does this by determining the time offset between the MTSAT SIS epoch, which is MNT, and UTC. The UTC, as determined by the Master Clock at the UTC provider, represents the approved time standard source for MSAS.

The M-TDS is an independent system located at the UTC provider facility. The M-TDS acquires the MSAS messages from the MTSAT within view of the UTC provider facility and performs a time difference between the MTSAT beginning-of-message epoch times and an accurate 1 PPS from the UTC provider time reference (the Master Clock at the UTC provider facility). The Master Clock also provides a stable 10 MHz frequency source to the M-TDS receiver.

The M-TDS contains an antenna, MSAS receiver, and modem. The M-TDS antenna receives the MSAS SIS from the MTSAT. The M-TDS receiver collects the MSAS SIS observables and forwards the MSAS navigation message and MNT/UTC offset data to the UTC provider processor. The output data string from the receiver contains the MNT offset data. The M-TDS modem provides the interface between the UTC provider processor and the MCS to communicate the MNT/UTC offset data back to the MSAS.

The data, produced by measuring each GEO satellite 1 PPS epoch with UTC (from the UTC provider), are collected and recorded for computation of correction parameters to MNT. The satellite epoch beginning time will be converted to MNT by utilizing the time offset and drift numbers from the MSAS SIS. The M-TDS then passes the values of all satellites being tracked to the UTC provider data acquisition system. The collection of MNT/UTC offset is performed by the M&C function for inclusion by the CPF in MSAS Message 12.

The M-TDS relates MNT to UTC (from the UTC provider). The primary purpose of the M-TDS is to provide the MNT/UTC offset data to the MCSs for the subsequent MSAS SIS broadcast to time users who require precise reference to UTC. Users at remote locations within the MSAS Service Volume can acquire the MTSAT SIS and utilize the correction parameters contained in Message 12 and their local receiver time to determine UTC to within an accuracy of 20 nanoseconds. Message 12 is not intended for navigation. Until the M-TDS is implemented, Message 12 will not contain any data.

MSAS AND THE TIMEKEEPING COMMUNITY

The MSAS will provide time within the Japanese Flight Information Region for the recording of all events. It will also provide a very stable timing signal for the timekeeping community. The MSAS timing signal will not be affected by SA. Since time is broadcast from the MTSAT, a GEO satellite, it will be relatively stationary to a user on the ground. Thus, a high-gain antenna can be used to provide a very good signal to the stationary user. The offset of MNT from UTC is transmitted within the MSAS navigation message. The signal will be available continuously.

Such a signal provides some unusual capabilities for the timekeeping community. **It should allow the development of more economical timing systems utilizing its signals.** Cheaper crystals can now be used in systems that rely on atomic standards as their flywheel while they integrate GPS time to remove the effects of Selective Availability. Because of the absence of SA, **it will be possible to almost instantaneously detect any pathological behavior in a system providing time.** With GPS, one has to wait to see if the transients are due to SA or anomalous clock behavior. If one is within the footprint of two GEOs within the same SBAS transmitting Message 12, one can have **an immediate redundancy check.** This can be used as an extremely robust check for many timed systems.

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System/Segment Design Document for MTSAT Satellite-based Augmentation System, SDRL Sequence No. MS202-01-002, dated 15 July 1998

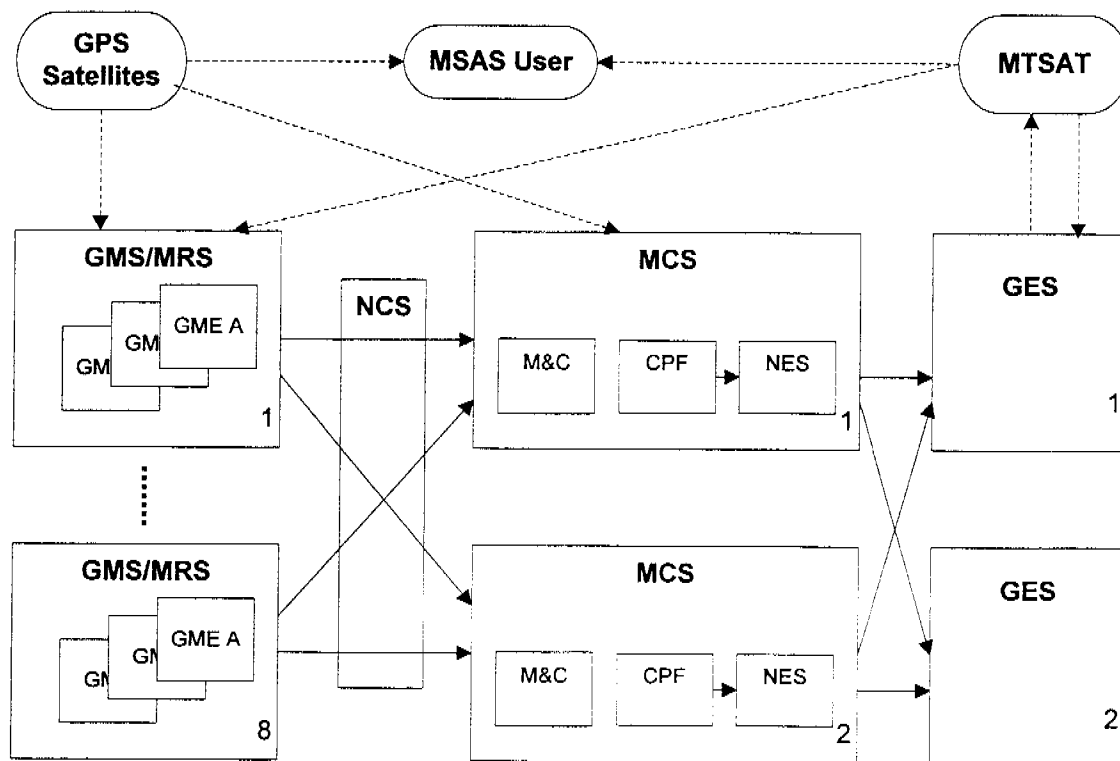


Figure 1. The MSAS Process

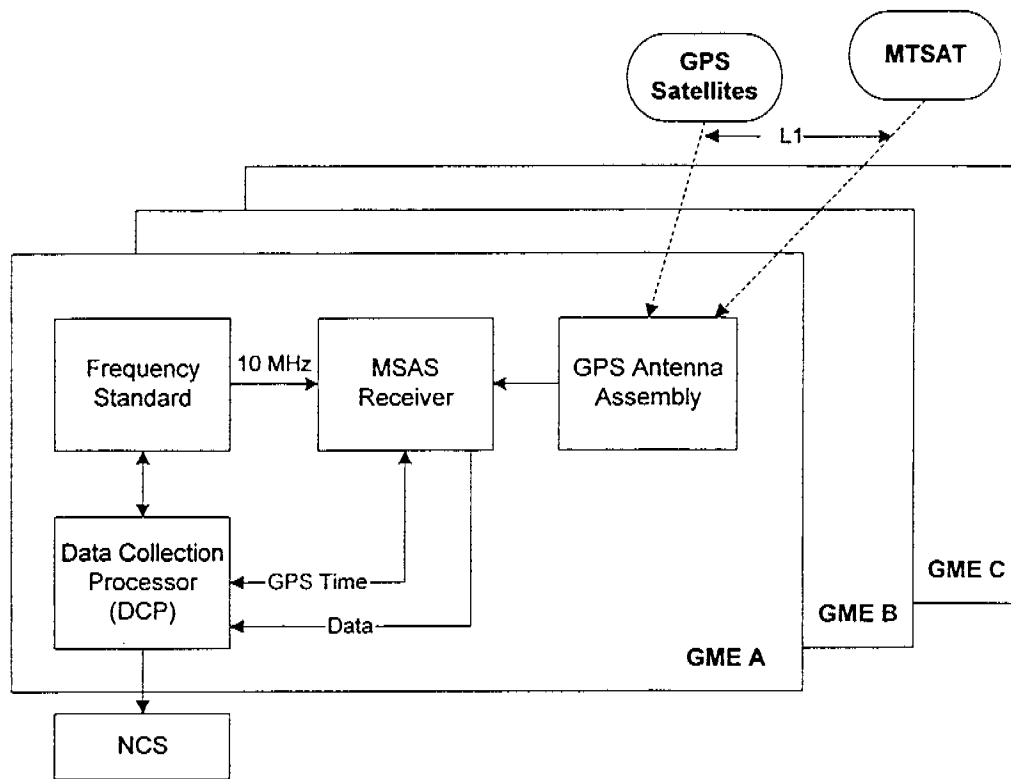


Figure 2. Role of the Frequency Standard in the GME Configuration

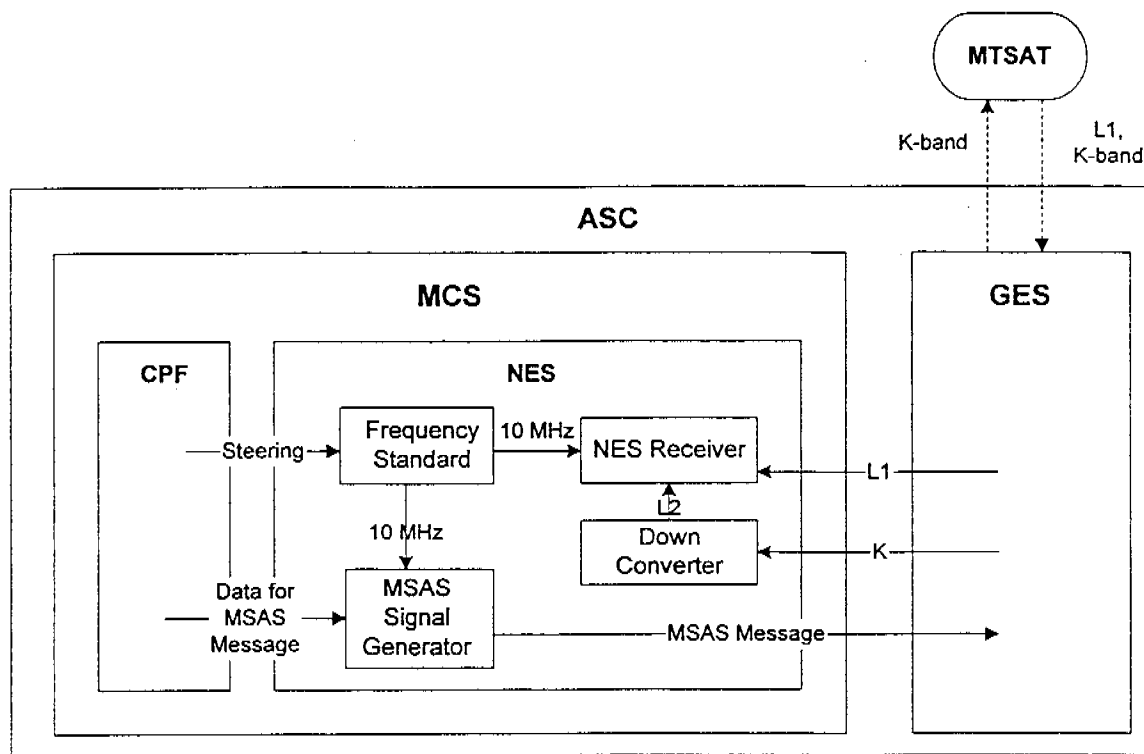


Figure 3. Role of Data and Time at the ACS