MAGELLAN PROJECT

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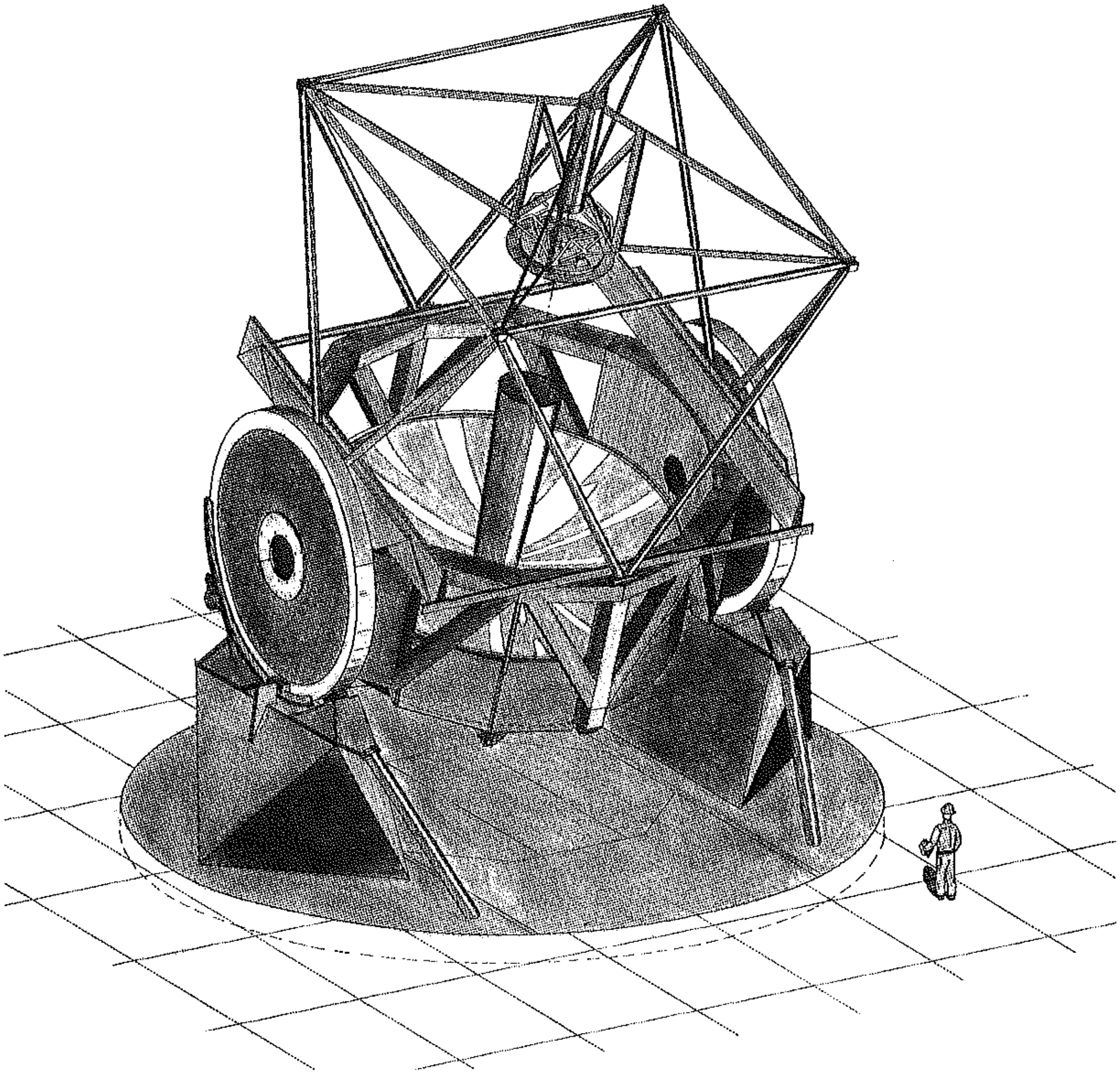

The Time and Frequency Requirements of the Magellan Telescope

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The Observatories of the
Carnegie Institution of Washington
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TABLE OF CONTENTS

Subject Page No.

1. INTRODUCTION

Due to the large size of the Magellan Telescope and the modern advancements in computer technology this telescope will be an altitude-over-azimuth (alt-azimuth) drive configuration, instead of the classical equatorial mounted telescopes presently used by The Observatories. In the new (to The Observatories) alt-azimuth drive configuration, the telescope pointing and tracking computer has to direct the altitude drive and the azimuth drive, to acquire, and smoothly track an apparent point across the sky. The pointing part of the computer's task will learn from each setting how to improve the accuracy of the next pointing command, however the initial setting for the night will need to be very close to avoid consuming too much of the observing time setting up.

The tracking part of the computer's task also needs several highly accurate correction inputs in order to smoothly accomplish its goal. An advantage of the alt-azimuth computer-controlled drives is that it already has the built-in capability to close the loop on various mechanical errors. This advantage should provide far superior pointing and tracking performance, never dreamed of with the existing open loop equatorial mounted telescopes.

The pointing and tracking computer will eventually need inputs on various telescope mechanical errors such as:

1. encoder offsets and periodic errors;
2. collimation errors (temperature dependent);
3. gravitational flexure and hysteresis;
4. nonperpendicularity of the telescope axes;
5. tilt of the azimuth axis from vertical.

The magnitude of the above mechanical corrections needed will not be exactly known until the telescope becomes operational, so they will not be discussed in this report.

This report will concern itself principally with the **time and frequency input requirements** of the Magellan Telescope to be located in Chile, South America (29 degrees south latitude, 72 degrees 42 minutes west longitude).

Modern observatories need Coordinated Universal Time (UTC) to do accurate short term scientific experiments (pulsar timing etc.) and to be able to correlate the timing of observations with other observatories. Thanks to recent technology, highly accurate UTC is now easy to obtain with a Global Positioning System receiver (see section 3, Navstar-GPS Satellite System).

UT1, astronomical time is required by the telescopes pointing and tracking computers to accurately compute the apparent star coordinates. Accurate UT1 time at the present time is more difficult to obtain than UTC.

2. DUT1, WHAT IS IT?

UNIVERSAL TIME: The classic definition of Universal Time (UT) is Newcomb's equation, which gives a linear relation between the Greenwich Sidereal Time (GST) and the Greenwich Mean Astronomical Time (GMAT). The GST is the observed hour angle of actual stars transiting the meridian, while GMAT is the civil time indicated by a "perfect" clock. Adding 12 hours to the GMAT gave the Greenwich Civil Time, and adding a time zone correction (usually an integral number of hours) gave the Standard Time, back when clocks were nowhere near as accurate as the rotation of the earth.

EARTH ROTATION: It was recognized in the late 19th century that the earth was slowing down in its rotation, and Newcomb's equation incorporated a secular term to account for the average rate of change of earth rotation time with respect to time defined by the orbital motion of the earth.

TIME SIGNALS: When HF radio time signals (WWV etc.) were first broadcast, the time basis was the Standard Time, and the accuracy was measured in milliseconds (and still is in South America). As the accuracy of clocks rapidly improved, their rate was adjusted to keep the broadcast time signals as close as possible to the actual Standard Time. It soon became obvious that the Standard Time defined by Newcomb's equation, the observed Sidereal Time, and the uniform time being delivered by the new improved atomic oscillators were not all the same. Short period noise in the rate of earths rotation could easily be observed when the quartz crystal time bases were replaced by the new atomic clocks.

ATOMIC TIME: Modern time standards now use cesium beam atomic clocks, which are several orders of magnitude more stable than the rotation of the earth. In 1972, the major time standard organizations agreed to broadcast time at a uniform rate, with a uniform definition of the length of the second. Thus, the length of the second was no longer related to the rotation of the earth, but to International Atomic Time. Also in 1972 Coordinated Universal Time (UTC) was allowed to accumulate at the same rate as International Atomic Time.

EPHEMERIS TIME: As noted above it has long been recognized that the earth's rotation was not uniform, but the orbital motion of the earth and other solar system bodies does produce uniform time to observational accuracy. This time scale is called Ephemeris Time (ET) to distinguish it from time based on earth rotation, which is called Universal Time. The actual difference between ET and UT is obtained from comparing transit observations with planetary positions, and can be deduced with varying accuracy over centuries. By design, the rate of International Atomic Time is that of Ephemeris Time to the best observational accuracy obtainable in 1972.

LEAP SECONDS: Since the broadcast time is known to be different from earth rotation, and what is really needed for practical civil timekeeping is the position of the earth, it was decided to introduce discontinuities in the civil time reckoning of integral seconds (leap seconds) and do this at announced times. The results is that the time signals broadcast would be uniform atomic time (useful to physicists doing short-term experiments), and the seconds would be labeled in a fashion very similar to the earth rotation time. Any second pulse broadcast would be within 0.7 seconds of that same named second of earth rotation time.

DUT1: This scheme would then short-change the celestial navigator and the astronomer by up to plus or minus 0.7 seconds by broadcasting a uniform time unrelated to the actual earth's rotational position. Since the earth rotates by 15 arc seconds in a second of time, this gave a 10 arc second error, and a navigational error of about 1000 feet. Fortunately, this difference is known quite well by observations, the Naval Observatory tracks the difference to millisecond accuracy. This difference is needed to schedule the insertion of leap seconds. Since the difference is known, and since earth rotation time is important to celestial navigation and astronomy, some time broadcasts include the difference between their UTC atomic seconds and the current earth rotation position. **DUT1** refers to information included in the National Institute of Standards and Technology (NIST) broadcast formats that provides the approximate difference between the UT1 astronomical time scale and the UTC atomic time scale. This information, DUT1 is currently broadcast to an accuracy of only 100 milliseconds, which is sufficient for navigational purposes. For modern astronomy the DUT1 time broadcast format needs to increase its accuracy to plus or minus 2 milliseconds. The astronomical community (at least those who are already using accurate alt-azimuth mounted telescopes) are requesting Roger Beehler (303) 763-8063 Time and Frequency Division of the NIST to improve their existing services to plus or minus 2 millisecond accuracy on their DUT1 broadcast.

POLAR WANDERING: Before deciding what accuracy is needed, we should consider what accuracy is obtainable. The other limit to accuracy in earth position at the arc second level is the location of the earth's crust with respect to the rotational axis. The actual instantaneous axis of rotation is very stable in space, its position being given by precession and nutation corrections to the milli-arc second level. Fluid motions within the earth allow the crust and thus all observatories to wander in a complex manner by about one arc second. There are two effects, one is a slight change in the latitude of the observatory, and the other a change in local sidereal time. Both have a full amplitude of about one arc second. This cannot be included in the DUT1 time correction however, because the effect is opposite in sign for two observatories on opposite sides of the earth. Without current information on the polar position, an observatory's observed zenith position will be uncertain to about plus or minus 0.5 arc second (0.03 second of time).

ACCURACY OF ALT-AZIMUTH POSITION: In the world of perfect mechanisms and textbook problems, the alt-azimuth telescope is pointed by first obtaining the position of the zenith in the sky, then transforming the desired position in the sky to the mount coordinates and moving the telescope to that position. But, life is not like that. The computer will need to know the errors in the mounting, its axis orientation, encoder errors, flexure, etc. Once all those are removed, we are left with the error in the position of the zenith axis in the sky. Clearly there will be an error in the east-west and north-south positioning due to the construction of the mount, and this is indistinguishable from a slight uncertainty in the latitude and the longitude of the site. Polar wandering changes both latitude and longitude, and the available knowledge of current sidereal time changes the effective longitude. Any long-term ground motion also changes this position, and the seismologists routinely measure tilts of several micro-radians occurring in time scales of weeks in active regions. To achieve an absolute pointing accuracy of 0.1 arc second, one would need to know UTC to 6 milliseconds, polar wandering to 0.1 arc second, and ground tilt variations to 0.5 microradian. All this is obtainable now, with the latest technology available. In practice, a few stars will be observed and the pointing corrections established by the computer, probably each clear night, or at least once a week. Long term accuracy without re-computing the local zenith correction cannot be better than about one arc second.

ACCURACY OF DUT1 VALUES: While the DUT1 correction is quite smooth on the 100 millisecond level, at the 1 millisecond level there is considerable noise. Weather systems can change the moment of inertia of the earth slightly, and there are well defined seasonal variations in rotation rate. One dramatic effect in the rotation rate of the solid earth results when the global average wind has a net flow east or west.

3. NAVSTAR-GPS SATELLITE SYSTEM

The Global Positioning System (GPS) was developed by the Department of Defense (DoD) to simplify accurate navigation. It uses satellites and computers to triangulate positions anywhere on earth. To triangulate, GPS measures distance using the travel time of a radio message. GPS "the new utility" may be the greatest achievement in navigation history and will most likely be the world standard for at least the next 20 years. Although navigation is its primary purpose, the new 10 billion dollar GPS does possess a most powerful by-product, time and frequency transfer.

The added benefit of time and frequency transfer is equally revolutionary, but not yet recognized as such. There are numerous time and frequency dissemination and synchronization sources providing both local and global coverage. However, the only global-coverage time keeping sources accurate to better than plus or minus 250 nanoseconds of UTC are presently limited to two sources: portable cesium beam atomic clocks that are carried to each users location and the economical (to the user) and more convenient GPS Satellite System.

The GPS is, at the present time, the most competent system for the distribution of precise time. This is despite the fact that it is not a completely operational system yet but should be by the time the Magellan Telescope sees first light. Each GPS satellite carries an ensemble of four onboard atomic clocks which are tracked and maintained traceable to UTC-USNO to better than plus or minus 100 nanoseconds.

Each GPS satellite is launched into a very precise orbit according to the GPS master plan, and because there is no atmospheric drag at the 10,898 mile altitude, the satellite will stay exactly in orbit. Since they go around the earth once every twelve hours, the GPS satellites pass over the DoD monitoring stations twice a day. This gives the DoD a chance to precisely measure their altitude, position, and speed. The variations they're looking for are called "ephemeris" errors. These errors are usually very minor and are caused by things like gravitational pulls from the moon and the sun, and by the pressure of solar radiation on the satellite. Once the DoD has measured a satellite's position, they relay that information back up to the satellite. Then that satellite will broadcast these minor corrections along with its timing information. GPS satellites not only transmit a pseudo-random code for timing purposes but they also transmit a "data message" about their exact orbital location and their system's health. All serious GPS receivers use this information to precisely establish the position of the satellite.

The most cost effective way to transfer UTC is through the use of an L-Band receiver designed to receive the GPS transmissions using their clear/acquisition (C/A) code. A single visit of a "portable" cesium beam-based clock to The Observatory remotely located in Chile would far exceed the initial cost of a single GPS receiver. There should be included in the GPS receiver a disciplined rubidium oscillator. This oscillator will provide the inherent frequency accuracy that can be derived from the time signals provided by the GPS satellites.

The final GPS network of 24 satellites (21 active and 3 spares) will eventually illuminate the entire globe. Discounting obstructions, the user can generally receive the signal as soon as the individual satellite rises 5 degrees above the horizon. The user will then have UTC to an accuracy within plus or minus 0.5 microseconds; improving almost immediately to plus or minus 0.25 microseconds or less.

In the "formative years" of GPS one external piece of data is needed, the receiver location. Initially the receiver location can be obtained from the local geographic survey and manually keyed into the receiver or fed in from the appropriate telescope computer through the RS-232 serial link. At a later date (about 1993) when all 21 of the active GPS Satellites are in position, the receiver will completely position itself using any four GPS satellites which need to be in view for just a few minutes to fix the position.

The GPS uses time of arrival measurements for the determination of user position. A precisely timed receiver clock is not essential for this determination because time is obtained, in addition to position, by the time of arrival measurements of four satellites simultaneously in view. If the altitude is known (e.g., for a surface user, like us) then only three satellites in view would be sufficient. The GPS is now operational for time and frequency transfer however at present, keeping accurate time and frequency does require a rubidium oscillator to work through the periods when no satellite is in view.

Later when GPS is fully operational, the rubidium oscillator is still essential for frequency transfer applications. This is because frequency stability and the resultant accuracy depends on an integration function and using the rubidium oscillator as a reference. In other words, it takes a considerable amount of sampling to obtain precision frequency information from the satellite signal. These time samples are converted to frequency and compared against the precision rubidium oscillator reference in the user set. A sampling of only 15 to 60 minutes will provide frequency accuracy in parts of ten to the twelfth power.

The DoD can purposefully degrade the accuracy of the GPS by implementing the Selective Availability (S/A) mode. The S/A is designed to deny hostile forces the tactical advantage of using GPS positioning. Given the worst case situation with the war time S/A in operation, the GPS still provides UTC to an accuracy that pleasantly exceeds the Magellan Telescopes's present UTC requirements. Although this new GPS break-through may give more accuracy than is presently needed, most all the alternate time and Frequency sources do not even come close to providing the desired UTC accuracies and/or coverage in South America.

4. DISCIPLINED RUBIDIUM OSCILLATOR

The rubidium vapor standard, like the cesium beam standard, uses a passive resonator to stabilize a quartz oscillator. The rubidium standard offers excellent short-term stability in a small package, at half the cost of a cesium beam standard. It is not self-calibrating, and therefore, during construction it must be calibrated against a reference standard such as a cesium beam frequency standard.

Operation of the rubidium standard is based on a hyperfine transition in rubidium 87 gas. The rubidium vapor and an inert buffer gas (to reduce doppler broadening among other purposes) are contained in a cell illuminated by a beam of filtered light. A photodetector monitors changes, near resonance, in the amount of light absorbed as a function of applied microwave frequencies. The microwave signal (6,834,682,614 Hz) is derived by multiplication of the quartz oscillator frequency. A servo-loop connects the photodetector output to oscillator so that the oscillator is locked to the center of the resonance line.

Resonance frequency is influenced by the buffer gas pressure and, to a lesser degree, by other effects. For this reason, a rubidium vapor standard must be calibrated against a reference standard. Once the cell is adjusted and sealed the frequency remains highly stable approaching the drift of UTC-USNO over longer periods of time (several months) when used in a GPS receiver.

5. KINEMETRICS/TRUETIME GPS-DC

Kinemetrics/Truetime of Santa Rosa, California (formerly located in Pasadena and a spin-off of the Caltech Geology Department) has developed several time control systems for use by geologists throughout Chile.

Their economical **Model GPS-DC** receiver transfers time and frequency from the GPS satellites to its synchronized clock via the satellite's L-band (1,575 MHz) radio frequency transmissions. The receiver has a front panel digital display that can give a visual readout of Coordinated Universal Time (UTC). Besides a visual display, the GPS-DC receiver provides IRIG-B time code, RS-232 interface and a 1 Hz reference pulse as the ultra-precise time mark. This Kinemetrics/Truetime GPS-DC receiver is a low cost alternative when compared to the early GPS receiving system originally proposed for the Keck 10-Meter telescope.

This GPS-DC receiver should be equipped with the optional Kinemetrics/Truetime **Disciplined Rubidium Oscillator.** This small oscillator is mounted inside the receiver and provides stable, ultra-precise 1, 5 and 10 MHz reference outputs on the back panel.

The Kinemetrics/Truetime **Model DCS-30** is a suitable 30 Volt DC backup power source for the GPS receiver. It has been specifically designed for use with the Model GPS-DC Receiver equipped with their Disciplined Rubidium Oscillator. The DCS-30 source supplies continuous, clean, noise-free 30 Volt DC power at all times from internal maintenance-free batteries. When AC power is lost there is no transfer time involved and, therefore, no interruption of power to the time and frequency system.

Kinemetrics/Truetime has an optional **Voltage Phase Angle** plug-in card for the Model GPS-DC Receiver. This option has been specifically designed for power utilities to provide vital information in determining power grid stability. This option samples the 60 Hz voltage supplied from the Observatories power grid and provides outputs of the voltage phase angle. The measurement range is 0 to 359.9 degrees with a 0.1 degree resolution.

Kinemetrics/Truetime also makes an IBM PC AT compatible computer plug-in card, the **Model PC-SG** that can input the IRIG-B signals directly from the above GPS receiver. This single card permits an externally supplied IRIG-B time code to be utilized as the reference time in a computer system. The internal timing is synchronized to the IRIG-B input code to within 1 microsecond. When the computer wishes to read the time from the PC-SG card a "freeze" command is sent and the time is saved in a scratch pad RAM. The time will remain static in the RAM until the user clears the freeze command.

The Kinemetrics/Truetime Model GPS-DC receiver, complete with a Disciplined Rubidium Oscillator will solve all the present and future high accuracy UTC requirements of the

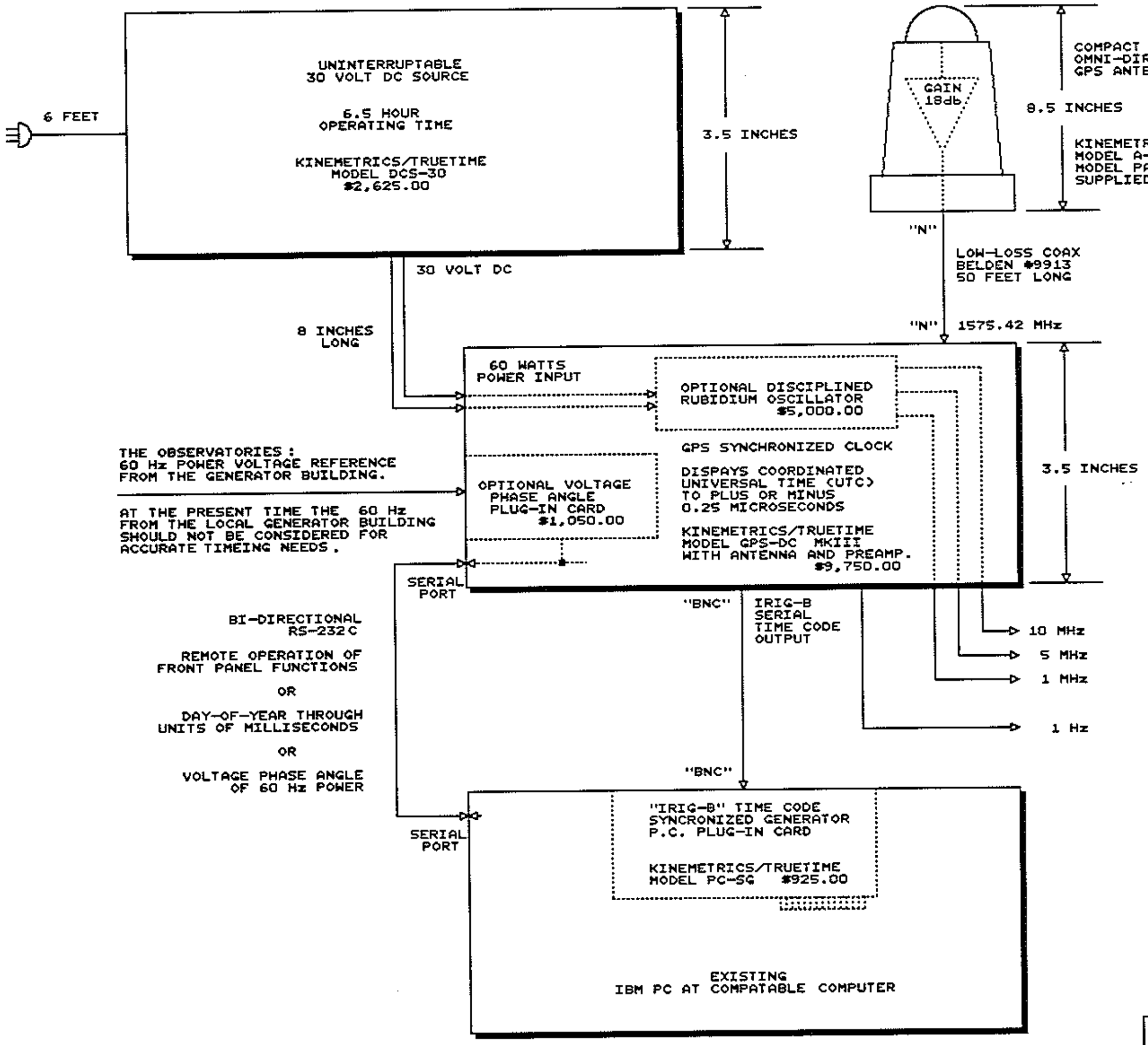
CLEAR/ACQUISITION (C/A) CODE, UTC-USNO

THE C/A CODE IS A SEQUENCE OF 1023 PSEUDO-RANDOM, BINARY, BIPHASE MODULATIONS ON THE GPS CARRIER AT A CHIP RATE OF 1.023 MHz.

GLOBAL POSITIONING SYSTEM (GPS)

24 GPS SATELLITES (21 ACTIVE WITH 3 SPARES) EACH WITH AN ENSEMBLE OF ONBOARD ATOMIC CLOCKS WHICH ARE TRACKED AND MAINTAINED TRACEABLE TO UTC-USNO TO BETTER THAN PLUS OR MINUS 0.1 MICROSECONDS

EACH SATELLITE IS AT A HEIGHT OF 10.898 MILES
ABOUT HALF THAT OF A GEOSYNCHRONOUS SATELLITE
ORBITAL PERIOD: 12 HOURS
ORBITAL PLANE: 55 DEGREES TO EQUATERAL PLANE
INDIVIDUAL SATELLITES PLANNED LIFE SPAN: 7.5 YEARS
NAME: NAVSTAR   MANUFACTOR: ROCKWELL INTERNATIONAL



PAGE 8

THE OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
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Magellan Project.

7. KINEMETRICS/TRUETIME 468-DC

It is recommended that an additional lower grade time receiver be used to supplement the GPS equipment. This back-up is useful to quickly coarse set the clock if there ever was a local outage (if there was not a GPS satellite view period for several hours, and the GPS receiver had stopped).

The reception of radio time signals in the High Frequency range (3-30 MHz) is nowhere near as dependable as hoped for in Chile. The High Frequency (HF) signals from WWV (Fort Collins, Colorado), WWVH (Kauai, Hawaii), JJY (Koganei, Japan), and LOL (Buenos Aires, Argentina) are all on the same frequency, and have different propagation paths that perform differently over a 24 hour period (more often than not interfering with each other). Even under optimum conditions, the above HF sources can only give a synchronization accuracy of plus or minus 5.0 milliseconds in South America.

Although the Low Frequency (LF) radio time signals from WWVB (60 KHz) Fort Collins, Colorado gives much greater accuracy (plus or minus 1.0 microseconds) it unfortunately does not give useful coverage outside of the continental United States and Canada.

The Geostationary Operational Environmental Satellite (GOES) receiver from Kinemetrics/Truetime **Model 468-DC** could be used to quickly reset the master clock easily to within a few milliseconds. More important, the 468-DC receiver also has the ability to read the DUT1 time code correction directly from the GOES EAST satellite's National Institute of Standards and Technology (NIST) time code transmissions. DUT1 is the correction to UTC, to obtain the current value of UT1 (Astronomical Time).

Unfortunately, the GOES satellite's time code presently only gives DUT1 to the nearest 100 milliseconds. The pointing and tracking computer would like this correction to at least plus or minus 2 milliseconds. This 468-DC receiver requires that a **RS-232C serial plug-in card option** from Kinemetrics/Truetime be installed for it to read out the above DUT1 correction.

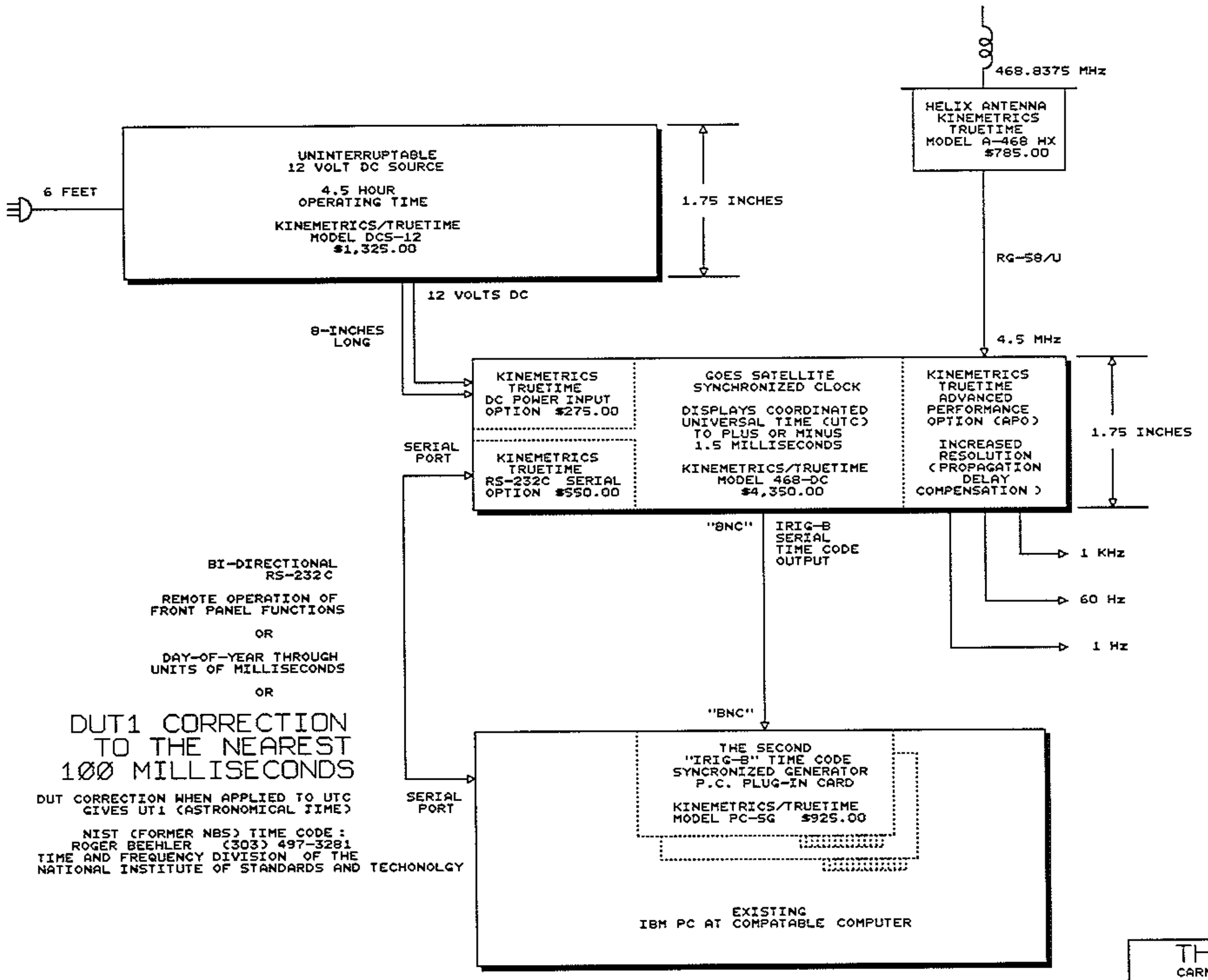
The same type of IRIG-B signals are also available from this receiver as they were from the Model GPS-DC receiver. The same type of previously described Kinemetrics/Truetime plug-in card, the **Model PC-SG** could be used to decode the time from the 468-DC receiver. This would enable the appropriate telescope computer to quickly and automatically coarse set the GPS-DC equipment's clock after an interruption.

The Kinemetrics/Truetime **Model DCS-12** is an uninterruptable 12 Volt DC power source designed for the 468-DC receiver. The DCS-12 power source supplies continuous, noise

GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITES (GOES)

THREE GEOSYNCHRONOUS SATELLITES LOCATED ABOVE THE EARTH'S EQUATOR:
GOES EAST = 75 DEGREES WEST LONGITUDE
GOES IN-ORBIT SPARE = 105 DEGREES WEST LONGITUDE
GOES WEST = 135 DEGREES WEST LONGITUDE

WE WOULD BE USING THE GOES EAST SATELLITE
WHICH IS LOCATED JUST A FEW DEGREES OFF OF DUE NORTH
FROM THE LAS CAMPANAS OBSERVATORY IN CHILE, SOUTH AMERICA.
(29 DEGREES SOUTH LATITUDE, 72 DEGREES, 42 MINUTES WEST LONGITUDE)



BI-DIRECTIONAL
RS-232C

REMOTE OPERATION OF
FRONT PANEL FUNCTIONS

OR

DAY-OF-YEAR THROUGH
UNITS OF MILLISECONDS

OR

DUT1 CORRECTION
TO THE NEAREST
100 MILLISECONDS

DUT CORRECTION WHEN APPLIED TO UTC
GIVES UT1 (ASTRONOMICAL TIME)

NIST (FORMER NBS) TIME CODE :
ROGER BEEHLER (303) 497-3281
TIME AND FREQUENCY DIVISION OF THE
NATIONAL INSTITUTE OF STANDARDS AND TECHONOLGY

THE OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
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-free 12 Volts DC power at all times from its internal maintenance-free batteries. A **DC input option** must be installed in the 468-DC receiver in place of the standard 120V 60Hz power supply.

The GOES 468-DC receiver is useful as a backup even though it may exhibit marginal accuracy for the UTC requirement of the Magellan telescope. This receiver's main function is to read out the DUT1 time code.

The still unresolved problem is that we would like to know the DUT1 correction to about plus or minus 2 milliseconds. This problem will exist until the NIST improves their existing time code services to the desired accuracy.

The International Earth Rotation Service (IERS) has a weekly publication (Bulletin-A) which incorporates Series 7 of the United States Naval Observatory (USNO)'s time service publications. The USNO Series 7 bulletin lists the earth orientation data (X, Y, UT1-UTC and nutation) to a far greater accuracy than we require.

The National Earth Orientation Service (NEOS) is a joint activity of the USNO and the National Geodetic Survey. They provide a telephone modem bulletin board which contains the latest data from the USNO series 7 bulletin. The 24-hour-a-day bulletin board phone number is 1 (202) 653-0597 with the requirements of up to 2400 bps, no parity, 8 data bits and 1 stop bit.

The problem with the use of a modem is the poor to nonexistent telephone service in the remote foothills of the Andes Mountains. If it technically could be done, 50 or more telephone calls to the Washington D.C. area from South America would, over a period of a year, be expensive.

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