Time Keeping and Clock Oscillator Requirement of the Mercury Laser Altimeter (MLA)

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1. Introduction

The Mercury Laser Altimeter (MLA) is required to measure the range from the spacecraft to the planet at a distance of 200 km to 1200 km. The required overall ranging accuracy is < 1.0 m at 200 km range.

There are primarily five factors that affect the ranging error: (a) receiver signal to noise ratio (SNR), (b) clock frequency uncertainties, (c) random clock phase noise, (d) receiver timing resolution, (e) laser pointing angle uncertainty. They should all be a small fraction of the overall 1.0 m error budget. Items (a) through (d) directly affect how we specify the clock oscillators.

The receiver ranging resolution should be much smaller than 1.0 m and most desirably comparable to the SNR limit, which is 0.05 m rms[*] under the best conditions. Given the MLA constraints, we picked a ranging resolution of 0.375 m (400MHz clock frequency), which gives an rms quantization error of 0.10 m. This is the same resolution as the Mars Orbiter Laser Altimeter (MOLA), which has been proven adequate.

The ranging error due to the clock frequency uncertainty has to be a fraction of the receiver ranging resolution, i.e., <<0.1m/200km = 0.5 part per million (ppm) rms. This type of ranging error is usually of the time scale of minutes to hours and cannot be easily removed via averaging. A tighter bound to this error source is warranted and 0.1 ppm is chosen as the requirement of the oscillator.

The random phase noise of the clock oscillator here refers to the relatively high frequency phase fluctuation that shows up as short term jitters in the clock waveform and may be averaged out over a short interval. The ranging error due to this noise should not be a dominating factor in the overall error budget. It should be much smaller than the receiver noise floor and the receiver quantization error. It should also be comparable with the inherent timing jitter of digital circuit, which is typically 50 ps rms. A reasonable choice for the clock oscillator specification is therefore 0.05 ns rms.

2. MLA Time Keeping Approach

A crystal clock oscillator will be used as the MLA master clock. The oscillator drives a multistage binary counter whose output states define the “MLA time”. The oscillator is left free run and its frequency constantly monitored against the spacecraft time ticks

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[*] rms = root mean square, which is the same as standard deviation in this case.

broadcasted over the bus. The counter output is latched in at every spacecraft time tick and at every laser firing. The spacecraft time base is maintained from earth and its long term frequency drift and the offset is constantly corrected. By comparing the number of MLA clock cycles elapsed between the spacecraft time ticks, we can have a precise knowledge of the MLA clock frequency at all times. The spacecraft time ticks recorded by MLA also give the offset between the MLA time reference (i.e. the origin) and the spacecraft time reference, and consequently the MLA time to the ephemeris, which is crucial in determining the MLA laser footprint on the planet. Since the traveling speed of spacecraft on the Mercury surface is about 2 km/s, an 1 ms uncertainties in the spacecraft time ticks translates to 2 m uncertainty in the laser beam footprint location on the planet, which is considered acceptable.

If the spacecraft time tick accuracy of +/-1 ms, an integration time of greater than 10,000 seconds is required to achieve <0.1 ppm accuracy in the knowledge of the average MLA clock frequency. The clock frequency accuracy of the time scale over which we measure the laser pulse time of flight (1.33 ms for 200 km range) is bounded by the oscillator short to mid term stability specification.

3. Time Ticks from Messenger Spacecraft

The raw spacecraft time is the so-called the mission elapse time (MET), which is generated by an on board OCXO and the MET counter. The OCXO free runs by itself and its drift and the associated MET value are monitored on earth during the periodic Messenger-earth data link every ~1.5 days. Spacecraft sends to MLA 1 pps ticks via hardware along with a real time announcement “at the tone, the time will be …”. Due to the frequency drift of OCXO, the time between the “1pps” ticks may not be exactly 1 second, but the fractions will be given in real time the announcement.

The real time announcement for the 1 pps ticks are the predicted times based on the past OCXO behavior and the MET offset. The accuracy of the prediction is +/-25 ms peak-to-peak with respected to UTC, which is warranted by the OCXO specification and the deep space communication network timing accuracy. MLA relies on this real time announcement to look up its position in the Mercury orbit and to time its operation. A better estimate of the times of the 1pps ticks will be given after the fact (~2 weeks) using the actually measured data. The accuracy of the post processed time ticks is +/- 1ms peak-to-peak. Note the error of this type tends to be long term and systematic. We have to assume the standard deviation (rms value) is close to peak to peak error over the time scale we are interested in.

4. Requirement for the Clock Oscillator

4.1. Frequency Stability over the Environment

Given the highly dynamic MLA thermal environment, temperature will be the major factor of frequency variation. It is also extremely difficult to predict the oscillator frequency based on the temperature sensor readings because of the rapid temperature transition rate (tens of degrees over 20 minutes), seasonal variation of the temperature profiles, and hysteresis between the actual crystal temperature and the external temperature sensors readings.

An ovenized crystal oscillator (OCXO) has to be used in MLA in order to meet the 0.1 ppm stability requirement without relying on correcting the frequency with temperature. An OCXO can easily achieve 0.1 ppm for a temperature range of –20 to +70 degree Celsius (Ref. 1).

A temperature compensated crystal oscillator (TCXO) is typically stable to 1 ppm over the same temperature range but the relationship between the frequency and the temperature is nonlinear and difficult to model accurately (Ref. 2). Some recent high end commercial TCXO can achieve 0.1 ppm but the selections are limited.

4.2. Frequency Stability at a Nominal Operating Temperature

The stability of crystal oscillators is often specified in terms of Allan Variance at a set of measurement intervals, e.g. 0.01, 0.1, 1 seconds. Allan Variance is defined as the mean square value of the frequency differences between two successive measurement intervals. Usually, Allan standard deviations normalized with respect to the average frequency are used in specifying the crystal oscillators, e.g. 1e-9 over 1s, 1e–10 over 10 s, etc. It has been shown (Ref. 3) that the variance of the frequency over an interval, tau, can be approximated as the sum of the Allan Variances of intervals tau, 2tau, 4tau, 8 tau, and etc, to the entire bandwidth of the system. Since we check (and correct) the oscillator frequency with the spacecraft time ticks every 10,000 s, we only need to sum up terms up to tau=10,000 s.

The Allan Variance for tau equal to 1ms to 1s is usually dominated by the white and the flicker phase noise of the oscillator and its value drops at least as fast as 1/tau. The Allan Variance stays nearly constant from 1s to about 100 s and then increases with tau because of the so called “random walk noises”. For a typical quartz oscillator, the normalized Allan deviation is well below 1e-9 at tau=10,000 s at a constant temperature (Ref. 2). As a result, the standard deviation of the frequency, which is the root of the sum of Allan Variances of tau, 2tau, …, is dominated by the first term of the Allan Variance and the rest contributing to less than 10%.

The gate time to be considered for MLA is tau=1.33 ms (200km range). To achieve a rms frequency error of less than 0.1 ppm, the normalized Allan standard deviation has to be less than 1e-7 at 1.33 ms. It can be approximated as <1e-7 at 1ms, which not only standardizes the measurement but also gives us some margin. We should also bound the Allan Variance such that it drops at least as fast as 1/tau for tau=1ms to 1 s and bound it to 3e-10 for tau=10,000 second to ensure the oscillator performance and quality is consistent with those typical in the industry. Since Allan variance over 10,000 seconds are difficult to measure, we can use the short term aging rate instead, i.e., <1e-9 /3 hours, which is easily achievable by most OCXOs on the market.

4.3. Phase noise and Spurious Output

A spectrum analyzer is required to detect phase noise and spurious output for frequency greater than 1 kHz, since some of those noises may not show up in the Allan Variance measurement, which is only performed at the few gate time intervals.

The phase noise of the oscillator output is given approximately as the ratio of the integrated side band noise spectral density to the average oscillator output frequency (carrier frequency). To achieve <0.05 ns jitter on a 400MHz clock, the total phase noise has to be 0.05ns/2.5ns time 2 pi, or -21dBc in the single side band phase noise integrated from 1kHz and up. Assuming the phase noise power spectrum is inversely proportional to the square of the frequency (white frequency noise) over >1kHz frequency range, the total phase noise is equal to the spectral phase noise density at 1kHz in dBc/Hz times 1000. In our case, we need the phase noise spectral density of the oscillator to be bounded to –51dBc/Hz at 1kHz, -71dBc/Hz at 10kHz, and –91dBc/Hz at 100kHz. The sum of all the spurious output at discrete frequencies (harmonics) should be much less than –21dBc. Another way to specify the total phase noise is to let the maximum jitter in the output waveform to be less than 50 ps.

References:

1. Mike F. Wacker, “Specify OCXOs to meet performance and cost demand,” *Microwaves & RF*, Jan. 1996, pp. 80-89.

2. John R. Vig, *Introduction to Quartz Frequency Standard,* Research and Development, Technical Report, CECOM-TR-97-3, U.S. Army Communications-Electronics Command, Research, Development and Engineering Center, Fort Monmouth, NJ, 07703-5000, June, 1997.

3. David W. Allan, Marc A. Weiss, and James L. Jespersen, “A frequency-domain view of time-domain characterization of clocks and time and frequency distribution systems,” Forty-Fifth Annual Symposium on Frequency Control, pp. 667-678.

Summary of Performance Requirement

- Stability over temperature: <0.1 ppm over the expected operating temperature range plus 5 degree margin

- Normalized Allan deviation at room temperature and minimum and maximum temperatures:
  <1.0e-7, 1ms
  <3.2e-8, 10ms
  <1.0e-8, 100ms
  <3.2e-9, 1s

- Phase noise:
  -51dBc, 1kHz
  -71dBc, 10kHz
  -91dBc, 100kHz

- Spurious output: <-21 dBc (sum of all spurious components)

- Mid term frequency stability: 1.0e-9 /3 hours

- Frequency stability vs. supply voltage: 0.05 ppm for <5% supply voltage variation