Demonstration of High Sensitivity Laser Ranging System

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Background:
The small size, high efficiency, high reliability and
direct modulation capabilities of semiconductor lasers
make them extremely attractive for space flight applica-
tions. In this paper we report on a high sensitivity semi-
conductor laser ranging system developed for the Gravity
And Magnetic Earth Surveyor (GAMES) for measuring
variations in the planet's gravity field [1].
The GAMES laser ranging instrument (LRI) con-
ists of a pair of co-orbiting satellites, one which con-
tains the laser transmitter and receiver and one with a
passive retro-reflector mounted in an drag-stabilized
housing. The LRI will range up to 200 km in space to the
retro-reflector satellite. As the spacecraft pair pass over
the spatial variations in the gravity field, they experience
along-track accelerations which change their relative
velocity. These time displaced velocity changes are
sensed by the LRI with a resolution of 20-50 um/sec. In
addition, the pair may at any given time be drifting
together or apart at a rate of up to 1 m/sec, introducing a
Doppler shift into the ranging signals.
An AlGaAs laser transmitter intensity modulated at
2 GHz and 10 MHz is used as fine and medium ranging
channels. Range is measured by comparing phase differ-
ence between the transmit and received signals at each
frequency. A separate laser modulated with a digital
code, not reported in this paper, will be used for coarse
ranging to unambiguously determine the distance up to
200 km.

Introduction:
Direct detection Laser diode-based ranging systems
reported [2,3,4] to this date have been designed to mea-
sure static range. The GAMES application requires a
unique ranging system capable of precise determination
of velocity changes in the presence of Doppler up to
1 m/sec. In order to achieve the accuracies for this mea-
surement, the transmitted signal is intensity modulated at
2 GHz with a modulation index of 90%, and the receiver
must be capable of single photon detection. We have
developed a breadboard ranging system with moving tar-
get capable of measuring these velocity changes.

Breadboard Description:
A block diagram of the ranging breadboard is shown
in Fig. 1 with nominal system parameters listed in table
1. Electrical drive signals for both the fine and medium
ranging channels are derived from the 10 MHz master
oscillator. Each channel has a phase lock loop (PLL)
which generates a local oscillator (LO) signal offset from
the main frequency by precisely 10 kHz. The 2 GHz and
10 MHz sinusoidal output signals are combined to drive
the laser diode along with a DC bias. The 820 nm optical
signal generated by the laser is reflected off the moving
retro-reflector target onto the photocathode of a photo-
multiplier tube (PMT). The output signal of the detector
is split into three channels and amplified. Two are filtered
for 2 GHz and 10 MHz respectively and the third is
reserved for photon counting.
The signal processing is similar to that described in
references [2] and [4]. Each ranging signal is independ-
ently downconverted to the 10 kHz intermediate fre-
quency (IF) by multiplying them with their respective
phase-locked LO signals. The fine and medium IF sig-
nals are then independently digitized at 40 kHz each by
a 16 bit analog-to-digital converter. The computer calcu-
lates phase for the signal by computing the average in-
phase and quadrature fourier components of the sampled
sinusoidal signal over 32 cycles (312 Hz) of the IF. The
phase is then converted to range. The fine ranging chan-
Figure 1. System block diagram of the GAMES laser ranging instrument breadboard.

The laser has a cyclical range of 75 mm while that of the medium ranging channel is 15 m. In order to satisfy the range resolution for the GAMES LR1 the 2 GHz cycle must be resolved to 0.25° (50 μm) while the 10 MHz cycle only needs to be resolved to 1° (40 mm) in order to overlap the fine ranging cycle.

Performance:
One of the main parameters which influences the accuracy of a range measurement is the number of cycles averaged. Fig. 2 shows this dependence for static range. For statistically independent data, the standard deviation should decrease by the inverse of the square root of the number of cycles averaged. A linear regression fit shows that when more than 8 cycles are averaged, the standard deviation decreases as $n^{-0.45}$ for the 2 GHz channel and $n^{-0.5}$ for the 10 MHz channel.

For our application the Fourier components computed over 32 IF cycles are recorded so as to be well above the Doppler frequency. After removing the constant

<table>
<thead>
<tr>
<th>Laser Transmitter</th>
<th>AlGaAs laser diode, 820 nm</th>
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<tbody>
<tr>
<td>Detector</td>
<td>MCP-PMT, Hamamatsu 3809U-11</td>
</tr>
<tr>
<td>Master Oscillator</td>
<td>10 MHz, TRAK, frequency drift $-10^{-13}$/sec</td>
</tr>
<tr>
<td>Cyclical Error</td>
<td>±75 mm in 37 mm cycle, due to image frequency interference at 2 GHz - 20 kHz</td>
</tr>
<tr>
<td>Fine Ranging Tone</td>
<td>2 GHz, 75 mm range cycle, 48% optical modulation depth</td>
</tr>
<tr>
<td>Med. Ranging Tone</td>
<td>10 MHz, 15 m range cycle, 6% optical modulation depth</td>
</tr>
<tr>
<td>IF</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Sampling Rate</td>
<td>80 kHz total, 40 kHz for each channel, 4 samples/cycle</td>
</tr>
<tr>
<td>ADC</td>
<td>16 bit, 2 channels, ±1 volt full scale</td>
</tr>
<tr>
<td>Phase measurement</td>
<td>compute I &amp; Q components from avg'd values at π/2 intervals, 312 times/sec (&gt;10x max. expected Doppler shift: 26.6 Hz)</td>
</tr>
<tr>
<td>Track</td>
<td>Computemotor LS-A, 3 m max. optical path length, controlled with Labview 3.1 software for windows, velocity: 100 μm/sec up to 1 m/sec, acceleration: 100 μm/sec² up to 3 m/sec²</td>
</tr>
</tbody>
</table>

Table 1. Summary of Ranging System Parameters
Figure 2. Range measurement standard deviation vs. IF cycles averaged. Top line is 2GHz range in microns, bottom line is 10 MHz range in meters.

Doppler velocity by linear regression, acceleration are computed by quadratic fit to 20 second long segments of the residues. The velocity changes induced by the gravity field are expected to take place over 10 second intervals and will allow us to fit the velocity data over this time period to achieve the required accuracy.

In Fig. 3 the target was computer controlled to move at 99 mm/sec for 25 seconds. A linear regression of the data yields a velocity uncertainty of 0.8 µm/sec. This is well within the accuracy requirement for GAMES.

Conclusion:

A semiconductor laser ranging breadboard has been developed for the GAMES mission. Preliminary results indicate that it is possible to achieve the required velocity resolution 20 µm/sec. A summary of system performance data will be presented.

References: