Using DSP Technology to Simplify Deep Space Ranging

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What is “Deep Space” Ranging?

- Provides a measurement of the distance from ground stations to a spacecraft under the following conditions:
  - Large distances. Anywhere from LEO (300 km) to Neptune (4.5 billion km).
  - Low signal. Down to -20 dB-Hz. But must also handle up to +50 dB-Hz.
  - Precise measurements. An actual measurement will depend on the ranging SNR, but the ranging system error sources RSS must be less than 1.25 m 1-sigma (1-way distance in meters).

- How are the ranging measurements used?
  - Spacecraft navigation teams use range to complement the doppler measurements. The spacecraft velocity implies an orbit location with error ellipses limited by carrier bandwidth. Range finds the absolute distance with an error ellipse based on signal strength. Using both increases orbit confidence. Range is crucial for:
    - Flybys, landings, and aerobraking.
    - Reduced tracking operations while in cruise mode.
  - Science teams study the media effects on range and doppler during planetary flybys to determine properties of the planet atmosphere. Similar studies are done for solar wind plasma studies.
DSN Ranging as a time measurement (not to scale)

Range - delays = 2 * R
R is the desired theoretical distance from Antenna Reference Height to spacecraft.

2 * R = C * {Range Measurement
+ N * Range Ambiguity - S/C delay
- Ranging Calibration
- (physical Z-height delays - ZDD)}
How DSN Ranging Works

- The Ranging system actually measures a phase delay
  - The ranging H/W modulates a ranging pattern on the uplink carrier.
  - The spacecraft re-modulates the ranging pattern onto the downlink, but does not regenerate the signal. The ranging tone is coherent, but power goes as $1/R^4$.
  - The receiver removes the doppler shift from the received ranging tone.
  - The ranging H/W correlates the received pattern against a copy of the current uplink pattern being transmitted. The phase shift that maximizes the correlation is the phase delay introduced by the round trip light time traveled.

- Ranging H/W must provide the following functions:
  - The highest frequency ranging tone (clock tone) is 1 MHz. Lowest frequency tone is 1 KHz.
  - The received ranging pattern must be digitized at 4 MHz to get the quadrature.
  - The range measurement must be time tagged with 1.0 µsec accuracy.
  - The ranging system must support 2 types of ranging modulation.
    - A series of square-wave tones transmitted sequentially (supported by current DSN system)
    - Pseudo Noise codes modulated onto the clock frequency (new requirement)
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DSP technology enables new ranging design

Old system: Code generation and Correlation in Hardware

Custom Interface Board
Sum and Resample at 4 MHz

Custom Correlator Board
In-phase, I
Accumulator 1
I = I + I(t)

Quadrature, Q
Accumulator 2
Q = Q + Q(t)

Delay period/4
Correlation for the specific generated Code

COTS CPU Board (Programmable)
Sample periodically
I & Q
Compute Phase
Range Phase

Received Range signal,
y(t) = x(t-RTLT) + noise(t) at 80 MHz

Custom Coder Board
Generates one type of code

New system: Code generation and Correlation in Software

Custom Interface Board (Programmable)
Sum and Re-sample at 16 MHz

COTS DSP Board (Programmable)
Select Code
Switch to j = index modulo N

y(t), index

FIFO
Read sample y(t) at index

bin[0] = bin[0] + y(t)
bin[1] = bin[1] + y(t)

......
bin[j] = bin[j] + y(t)

N = period of x(t)

Correlation with any Code, x(t):
I[k] = Σ bin[j+k] * Code[j]
Q[k] = Σ bin[j+k-N/4] * Code[j]
Compute Phase

Range Phase

SHB-5
When did DSP technology catch up?

- The old ranging (the Sequential Ranging Assembly, SRA) is still working in the DSN. It was designed using late 1980’s technology. You could not buy COTS processors that could handle 4 MHz FIFO inputs while also accumulating the samples in a bin.
- For the SRA design, it was cheaper to make custom correlators that could produce an I and Q for the processor to sample.
- JPL did a breadboard feasibility study in 1997-98 that proved that COTS DSPs approaching the 120 MHz processing speed could handle up to 16 MHz FIFO input.
- As part of the NASA and JPL’s Network Simplification Project, the ranging functions will be consolidated into the receiver (1 pair of ranging boards) and the transmitter (1 pair of ranging boards) subsystems.
- The separate rack (2’x2’x6’) dedicated to SRA and its controller will be replaced by 4 VME boards, 2 of which are COTS.
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Design handles Uplink and Downlink Functions

H/W domain

- Ranging Interface Board
  - D/A Converter & Amplifier
    - 16 Msamp/s
    - 16 bits Range Mod.
  - Sum and Re-sample at 16 MHz
    - 16 Msamp/s
    - 16 bits Range Signal
  - Timing Circuit & Control
    - low rate
    - 16 bits read/write

S/W domain, includes code generation and the correlation

- COTS (Pentek 4290) Ranging Processor Board
  - Configuration Information
  - N = period of x(t) * Fc * Q/128
    - bin[0] = bin[0] + y(t)
    - bin[1] = bin[1] + y(t)
    - ....
    - bin[j] = bin[j] + y(t)
  - Range Modulation signal, x(t)
  - Received Range signal, y(t) = x(t-RTLT) + noise(t)
    - With 1 PPS in high bit
  - Extract high bit
  - Command to read periods
    - if high bit = 1: read period values, record sample ID
    - high bit sample ID
    - Start switch at high bit sample ID, index = 0, time = Tr
  - FIFO
    - y(t), index
    - index++
  - FIFO
    - y(t)
    - Read sample y(t) at index

I/O addr.
Advantages of New Ranging Design

- Less Custom H/W = Cheaper cost.
- Less H/W plus DSP boards that are smaller than older processor means less rack space, fewer spares, fewer cables, less cooling needs.
- The design puts the ranging code generation into the software. The new ranging system can be programmed to use any code modulated onto 1 MHz.
  - One set of H/W will support the old sequential tones and the PN tones.
  - PN needed to support new spacecraft transponders with regenerative ranging.
- DSP has 16 MHz FIFOs, providing for upgrade to 4 MHz range tones.
- DSP FIFOs and address for I/O control provide a very clean interface agreement between the COTS H/W and custom H/W.
  - Allows for future changes to one with changing the other.
  - Can upgrade to future DSP COTS products.
- DSP Boards are programmed in ‘C’ and have good development tools.
- Programmers can be found for DSP platforms, helping maintenance.
Some Prototype Results

- Tests used First Production Unit (FPU) H/W and prototyped S/W. H/W is:
  - Ranging Processor Board (RPB): Model 4290 quad TMS320C6201 processor DSP board from Pentek Inc. Includes Pentek Model 6227 mezzanine interface board.
  - Ranging Interface Board (RIB): JPL design, board produced by vendor.
  - RRP Interface Board: JPL design, board produced by vendor.

- Downlink demo at Demonstration and Test Facility DTF-21:
  - Ran the SRA and new ranging (downlink only) in parallel.
    - Used the SRA for tone generation and input to exciter. Exciter output to 2 receivers
    - Configured both the SRA and the new ranging to receive inputs from different receivers.
  - Demo at DTF-21 proves:
    - Downlink H/W requirements are met by RPB, RIB, and RRP Interface Board.
    - RPB is fast enough for prototype S/W to keep up with samples, correlate the signal, and manage the RIB in realtime.

- Bldg 238 lab test validated uplink ranging H/W and RRP chassis compatibility.
Test Results from DTF-21 downlink demo Oct. 1, 1999

SRA and RRP ranging (downlink only) run simultaneously on the same SRA modulation output. The changes show increase in cable length relative to baseline:

<table>
<thead>
<tr>
<th>Cable</th>
<th>Expected Delay</th>
<th>SRA Variance</th>
<th>RRP Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>9.1 range units</td>
<td>-0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Long</td>
<td>42.1 range units</td>
<td>2.6</td>
<td>1.0</td>
</tr>
</tbody>
</table>

SRA and RRP ranging measured the same ranging signal to noise density, 41 dB-Hz. Hardware meets downlink baseband requirements.

SHB-10
Test Results from bldg 238 lab. Oct. 12, 1999

Ranging test incorporated range boards into first-of-a-kind RRP. No problems were seen. Test verified uplink ranging tone generation from FPU ranging hardware. Ranging test done at 63 dB-Hz (higher than requirement) to discover the limitation from error sources in this configuration. The hardware is meeting (and exceeding) the requirement, in this configuration.