Virtual Research Presentation Conference

Rapidly Reconfigurable Design, Analysis and Verification Capability for Next Generation Terminal Descent Sensors

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Program: Topic R&TD

Assigned Presentation # 152

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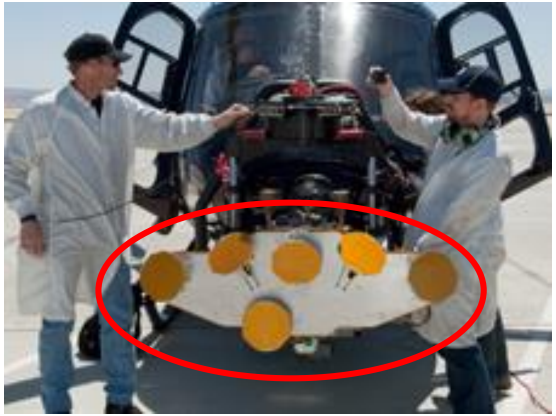
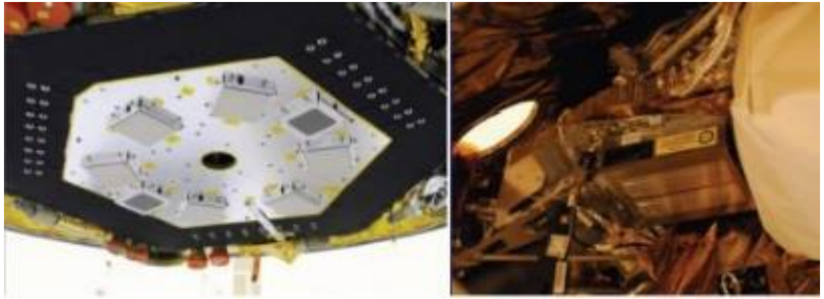
Introduction

- Guidance, Navigation & Control (GN&C) depends on an array of sensors to guide a spacecraft down to the surface of any planetary body
- JPL flown landing radars from C-band (5GHz) to Ka-band (35GHz) on numerous previous missions (Phoenix, MSL, Insight, M2020)
- Some radars were commercial (Honeywell, used on Phoenix and Insight), while others were built in-house (MSL, M2020)
- Each mission has its own requirements for Entry-Descent-Landing (EDL), driving the choice of GN&C sensors
- The NASA STMD Roadmap TA 9.2.7.1 identifies the need to "reduce size, mass and power of radar sensors to meet the requirements of future missions"
- This R&TD aimed to develop a rapid prototyping capability that integrated software simulation and performance evaluation tools with a Software-Defined Radio enabled hardware testbed to perform closed-loop (hardware-in-the-loop) simulations



MSL TDS



Insight Landing Radar

Problem Description

- TDS, a 6-beam pulsed Doppler radar – was designed specifically for MSL (and now M2020), where size, mass and power were not the driving requirements
- Path to a smaller, lighter TDS:
    - *Fewer beams* (3 instead of 6?) – this goes some way in achieving a smaller instrument, but, that only goes part of the way
    - *Higher operating frequency* (W-band instead of Ka-band) - biggest pay-off (potentially a 3-times size reduction compared to TDS WITHOUT reducing beams)
- Higher operating frequencies have their own challenges!
    - *Velocity folding (function of wavelength)*
    - *Dust susceptibility*
- However, these are not insurmountable challenges
    - *Innovative 'channel' utilization: add a CW channel in addition to pulsed-Doppler to mitigate velocity folding*
    - *What are the hardware constraints to achieve this? What is our trade-space to achieve this?*
- Will this work?
    - *Seems promising, but…..we need to develop simulation and prototyping tools to evaluate these new approaches!*

6-beam Ka-band TDS

3-beam Ka-band TDS

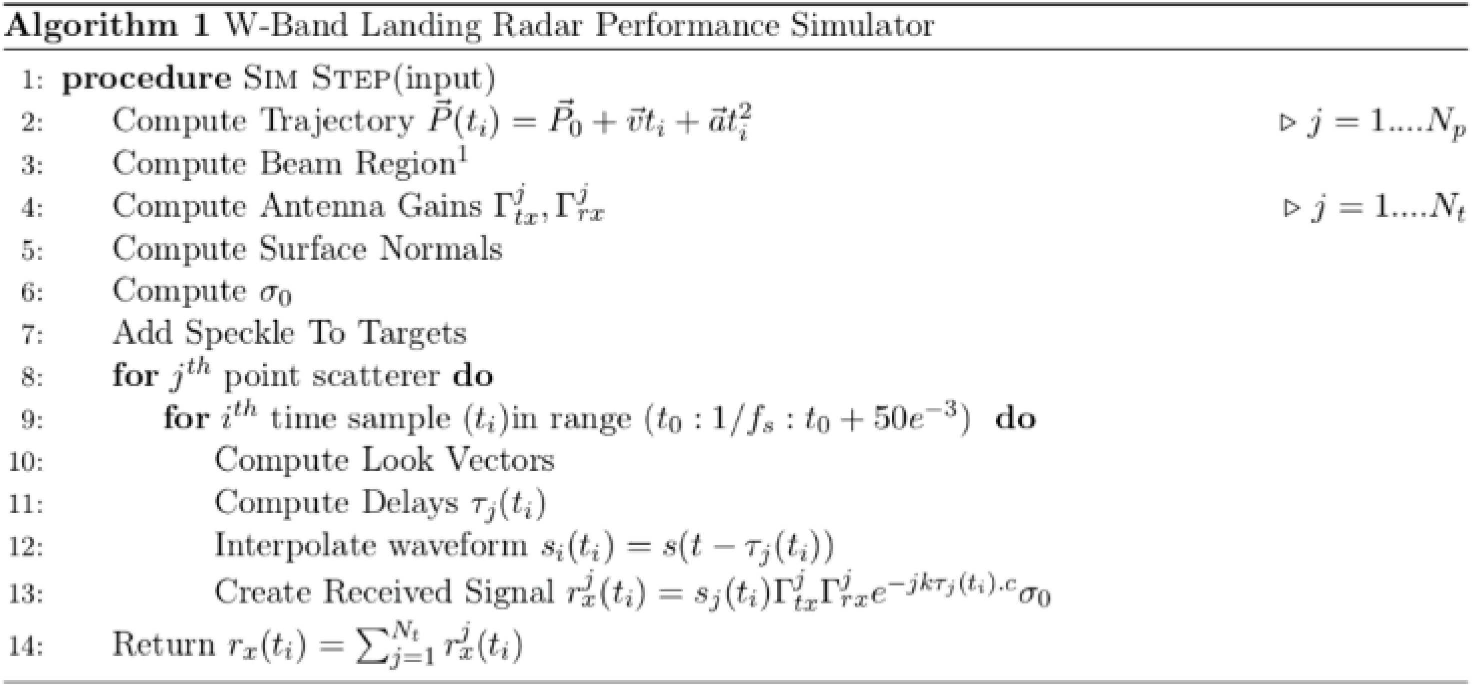
6-beam W-band TDS

Methodology

- This R&TD effort had 2 main tasks:
  - Develop generalized landing radar design and performance evaluation tools
  - Develop an agile hardware platform capable of testing and demonstrating landing radar instrument concepts
- Performance Evaluation Tools
  - The tool – WBLRSim - developed in the R&TD is generic, not tied to a specific mission, EDL profile or hardware implementation
  - Time-domain point scattering approach, allowing the simulation of varied radar architectures that include pulsed-Doppler, Continuous Wave (CW), Frequency-Modulated Continuous Wave (FM-CW) amongst others
- Agile Hardware Platform
  - Built around a commercially available Software-Defined Radio (SDR)
  - Two RF front-ends (Ka-band and W-band) were added to the SDR to demonstrate capability at different operating frequency
  - Multiple applications for the platform:
    - Performance verification for the simulator
    - Test new radar algorithms
    - Operate as a Distributed Target Simulator (DTS) to evaluate and verify performance of various RF front-ends
    - Operate as a complete radar system for field demonstrations

Performance Simulator - WBLRSim

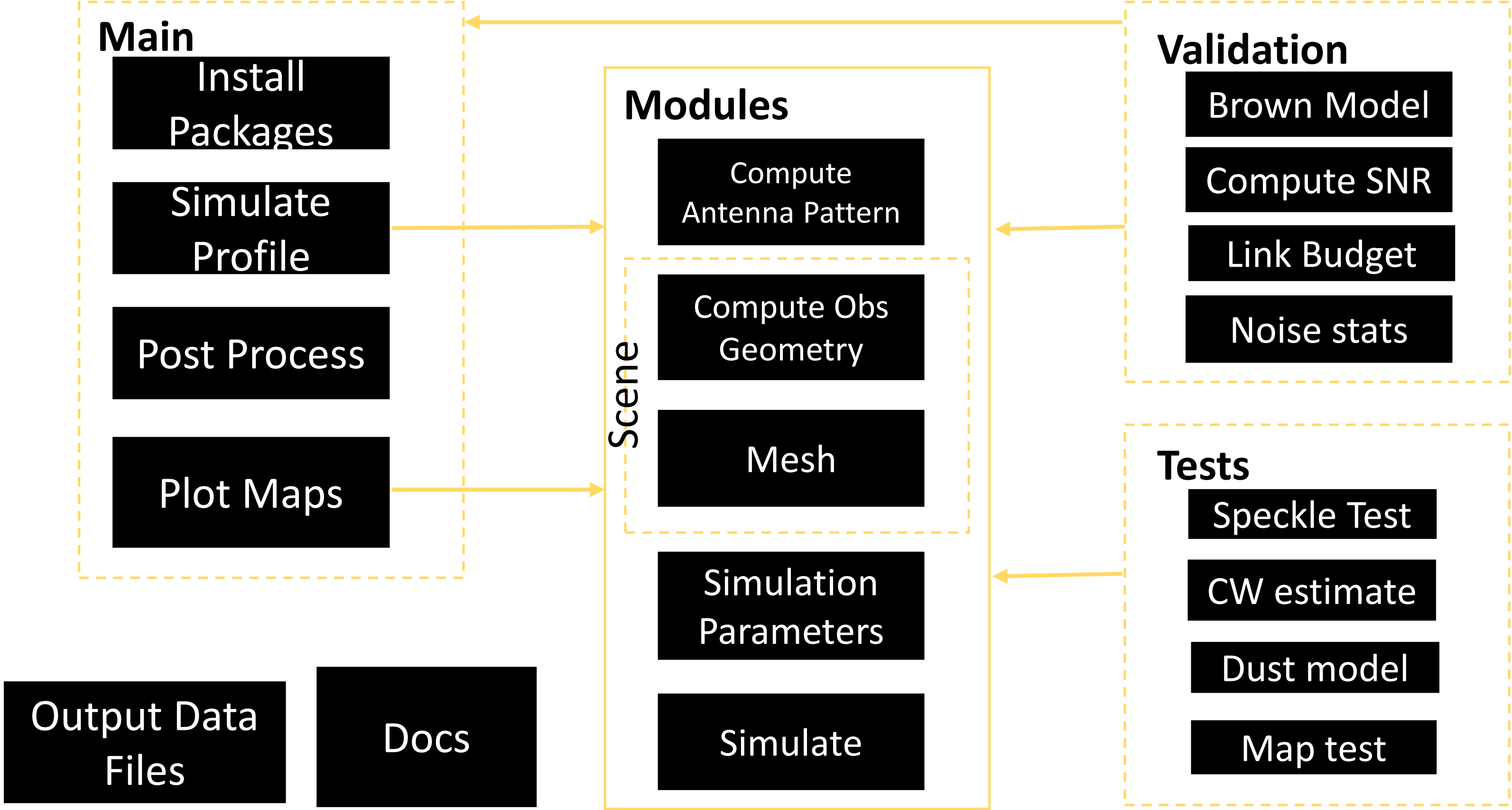
- WBLRSim is written in the programming language Julia, which is designed for high-level, high performance parallel computing



Algorithm 1 W-Band Landing Radar Performance Simulator

```
procedure SIM STEP(input)
    Compute Trajectory $\vec{P}(t_i) = \vec{P}_0 + \vec{v}t_i + \vec{a}t_i^2$        ▷ $j = 1....N_p$
    Compute Beam Region$^1$
    Compute Antenna Gains $\Gamma_{tx}^j, \Gamma_{rx}^j$        ▷ $j = 1....N_t$
    Compute Surface Normals
    Compute $\sigma_0$
    Add Speckle To Targets
    for $j^{th}$ point scatterer do
        for $i^{th}$ time sample $(t_i)$in range $(t_0 : 1/f_s : t_0 + 50e^{-3})$ do
            Compute Look Vectors
            Compute Delays $\tau_j(t_i)$
            Interpolate waveform $s_i(t_i) = s(t - \tau_j(t_i))$
            Create Received Signal $r_x^j(t_i) = s_j(t_i)\Gamma_{tx}^j\Gamma_{rx}^j e^{-jk\tau_j(t_i).c}\sigma_0$
    Return $r_x(t_i) = \sum_{j=1}^{N_t} r_x^j(t_i)$
```

WBLRSim - Implementation



Main

- Install Packages
- Simulate Profile
- Post Process
- Plot Maps

Modules

- Compute Antenna Pattern
- Scene
  - Compute Obs Geometry
  - Mesh
- Simulation Parameters
- Simulate

Validation

- Brown Model
- Compute SNR
- Link Budget
- Noise stats

Tests

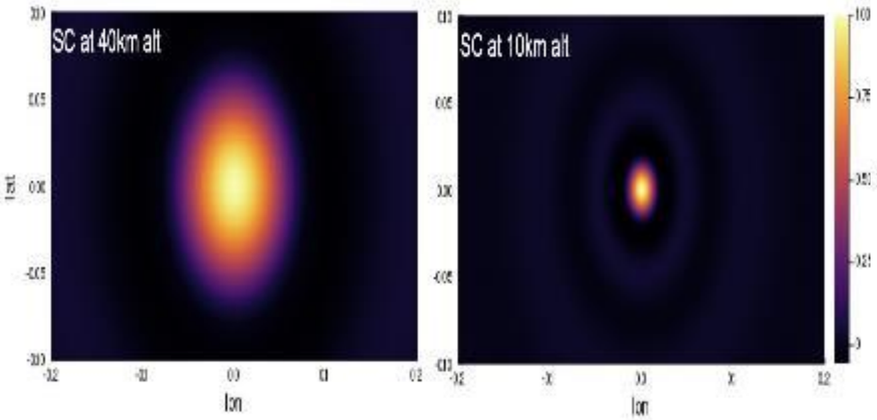
- Speckle Test
- CW estimate
- Dust model
- Map test

Output Data Files

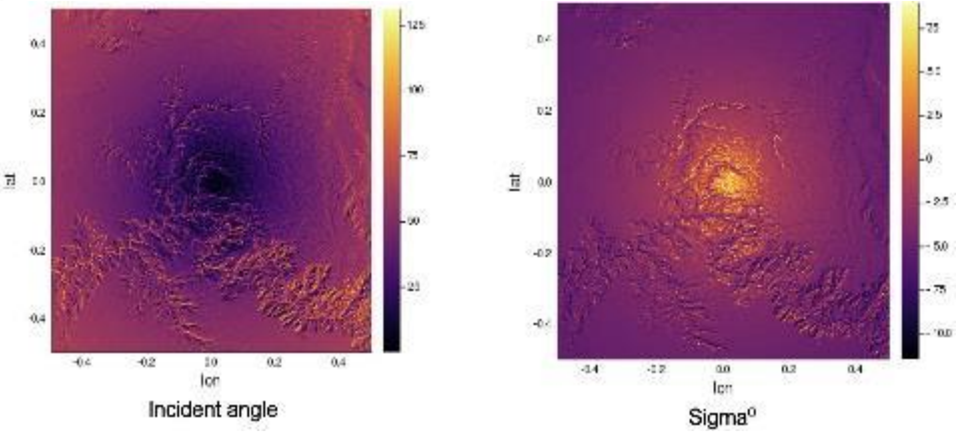
Docs

WBLRSim - Results

- Simulations were run for various scenarios
- The output from each module of the simulator can be saved and visualized for further analysis
- Shown below are two such outputs:
  - Antenna patterns projected onto the surface of a planet from the spacecraft at two different altitudes (Compute Antenna Pattern module)
  - Surface reflectivity at specific incidence angles. Depending on the EDL profile, the incidence angle map can be updated (Compute Observation Geometry module)



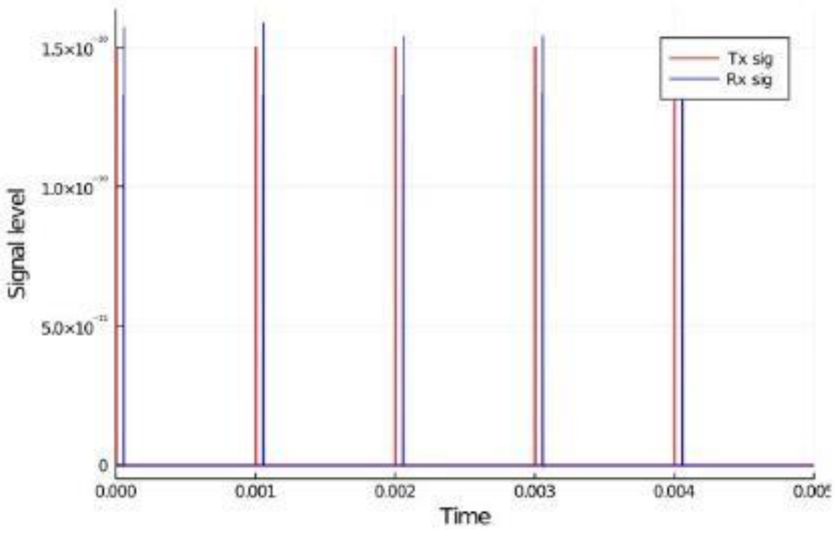
Antenna Pattern Projected onto the Planet Surface



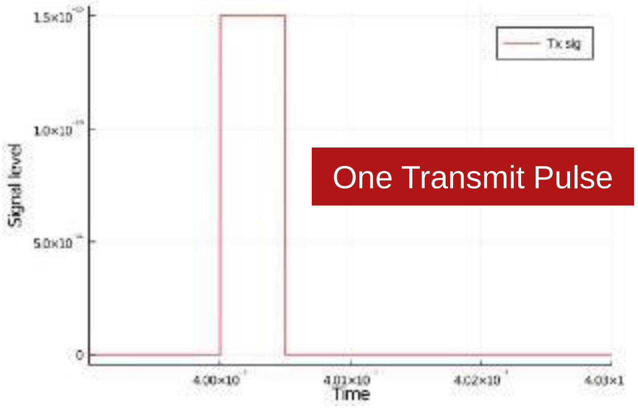
Incidence Angles and Surface Reflectivity for the Grand Canyon

WBLRSim - Output

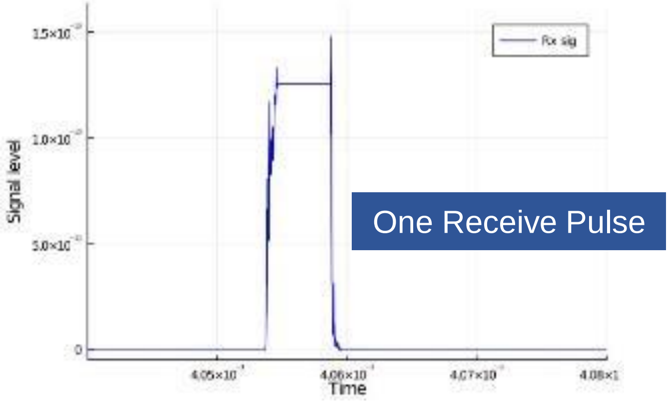
- The simulator is run in 50msec increments
- Shown below is the output of the simulator for one 50msec block



Transmit and Receive Pulses in One Simulation Block



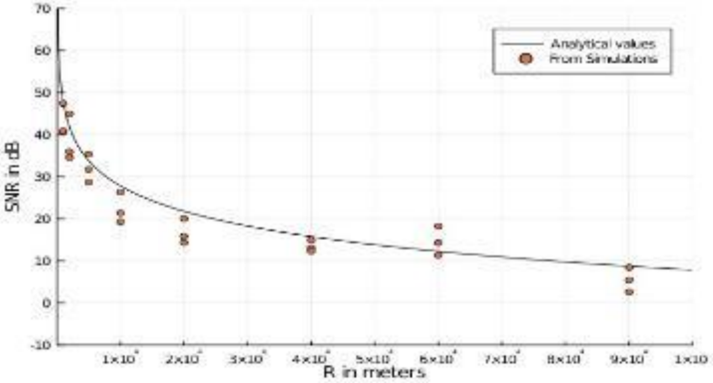
One Transmit Pulse



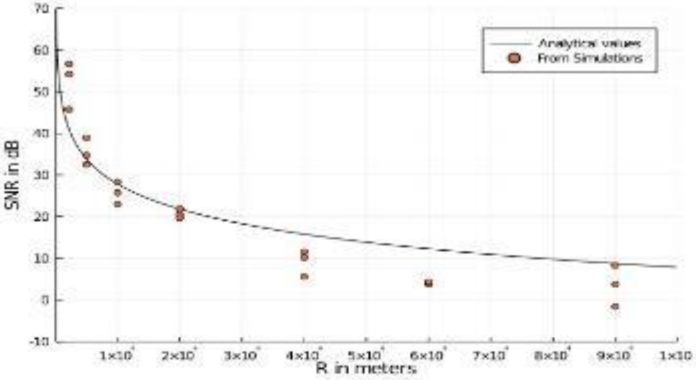
One Receive Pulse

WBLRSim – Validation

- Simulator validation – an important step in the development – was done using two approaches
    - Link Budget Analysis
        - Simple, closed-form analytical approach
        - Accounts for all the gains and losses in the system including propagation losses and surface reflectivity
        - Does not accounts contribution of surface scatterers outside the antenna main beam or randomness of targets or speckle
    - A comparison of WBLRSim and the Link Budget Analysis shows good agreement
    - When a Digital Element Model (DEM) is included in WBLRSim, the results deviate from the Link Budget Analysis since the analytical model does not account for target randomness or include effects of scatterers outside the main beam of the antenna



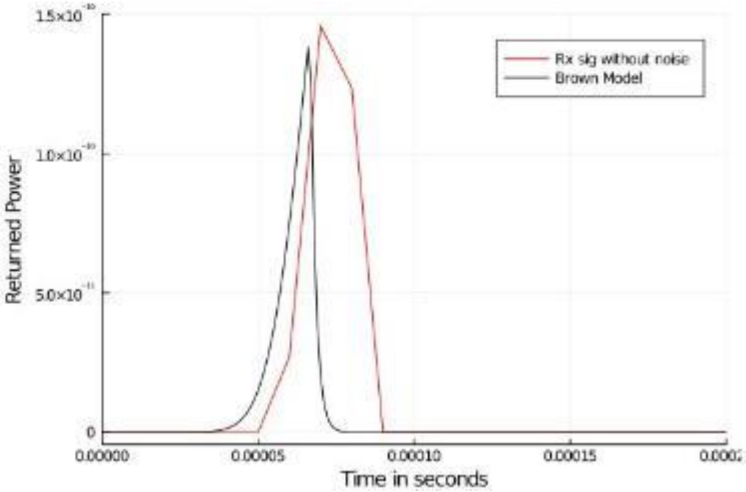
Comparison with Link Budget – no DEM



Comparison with Link Budget –DEM included

WBLRSim – Validation

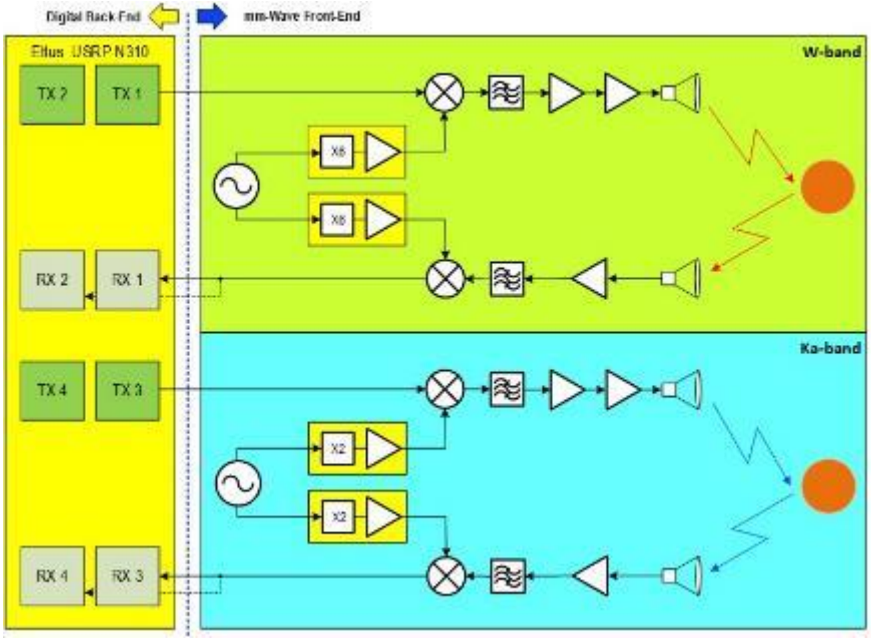
- Brown Analytical Model Comparison
  - Commonly used in radar altimetry
  - Theoretical model for short pulse scattering from a statistically random planar surface
  - Closed form solution based on the convolution of three terms
    - Point target response, which represents the original pulse
    - Surface response, which includes the altimeter antenna pattern
    - The probability density function of the specular heights
  - The shape of the received signal from WBLRSim shoes good agreement with the Brown model
  - Further analysis is required to investigate the differences in pulse width and amplitude



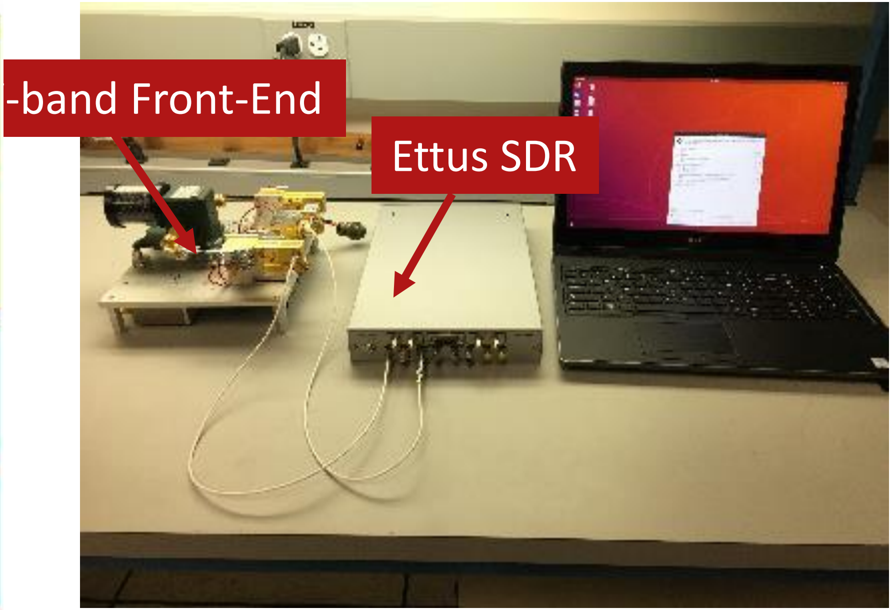
Brown model comparison with the received pulse

Hardware Test-Bed

- Hardware test-bed is built around a commercially available Software Defined Radio (SDR) – the Ettus USRP N310
- The test-bed (as currently configured) has Ka-band (35GHz) and W-band (94GHz) front-end units, allowing the test-bed to be operated as two independent radar systems



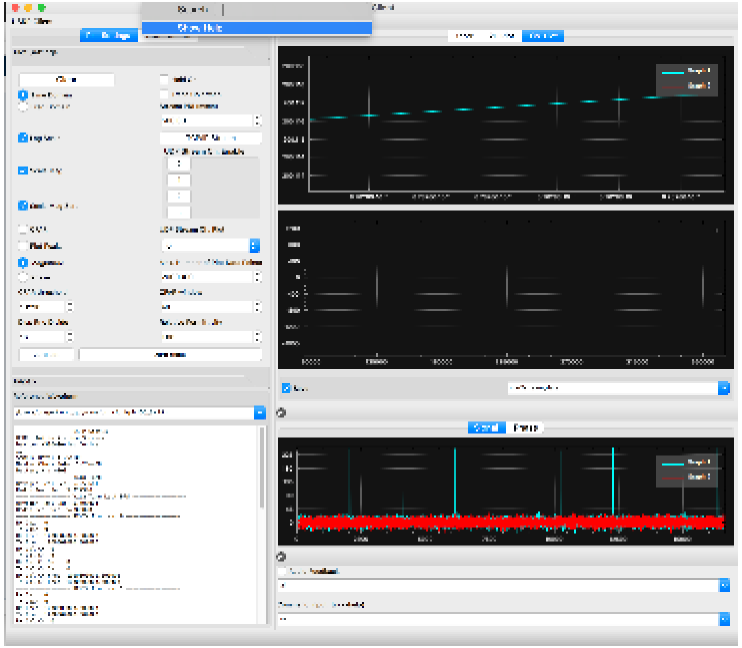
Test-bed Block Diagram



W-band Test-Bed

Hardware Test-Bed

- The SDR can support 4 Transmit/Receive channels simultaneously with an instantaneous bandwidth of 125MHz per channel
- A software defined radar (SDRadar) is implemented in SDR hardware is achieved through a combination of software and FPGA firmware, providing agility to test various radar implementations
- In the current configuration, the SDR supports Continuous Wave (CW) and pulsed Doppler operation (both modes can be operated simultaneously)
- Range and doppler velocity estimation is implemented on-board
- A custom-designed user-interface allows the user to configure individual channels, upload waveforms, receive and visualize ***(in real-time)*** signals

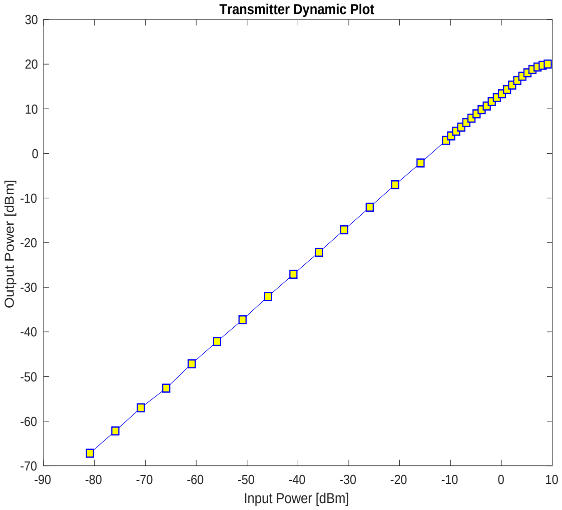


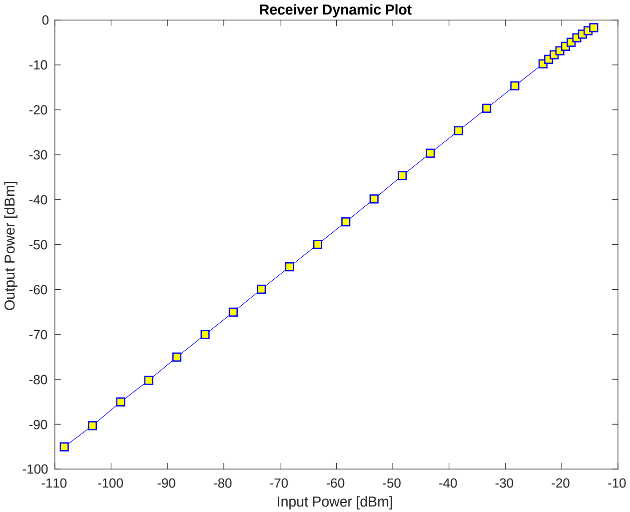
SDR User-Interface

Hardware Test Bed – Integrated Assembly Tests

- The test bed was assembled using Commercial Off-The Shelf (COTS) components
- Initial bench-top tests were performed to verify key performance characteristics of the system

Parameter	Ka-Band	W-Band
Output Power	+33dBm (2W), +24dBm low-power option	+33dBm (2W), +22dBm low-power option
Noise Figure	2.4dB	3.5dB
Number of Tx/Rx	1/1	1/1
RF Doppler Measurement Accuracy	0.01ppm	0.01ppm





Hardware Test Bed – Field Test

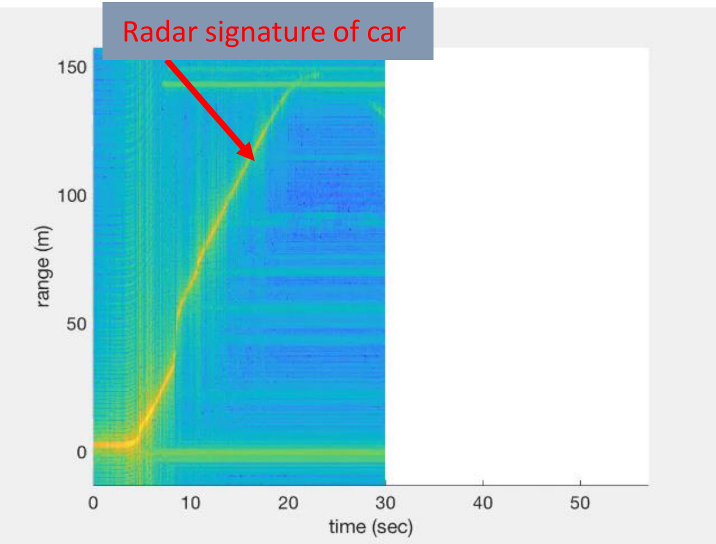
- The baseline plan was to operate the Ka-band and W-band systems from an Octocopter to demonstrate the ranging and velocimetry capabilities of the test-bed
- Due to COVID, the campaign had to be descoped
- In preparation for the field tests, we conducted an outdoor 'first light' test in the JPL East lot with the W-band system in December 2019

OS1 LIDAR

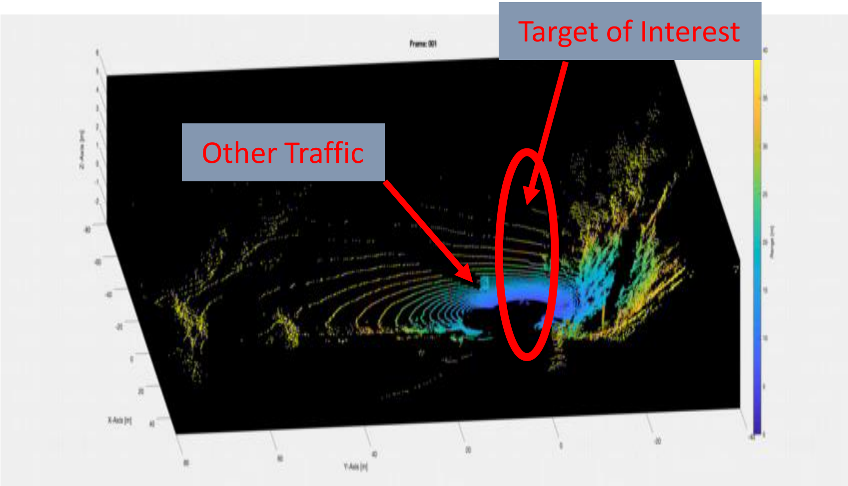
W-band System

Hardware Test Bed – Field Test

- We procured a small 16-beam LiDAR system (max range ~100m) – used for self-driving cars – to validate the radar measurements
- We operated the LiDAR along with the radar in the parking lot and measured the distance and velocity of a car driving towards and away from the radar


Radar signature of car

Range estimates from the Radar


Target of Interest

Other Traffic

Range estimates from the LiDAR

Summary and Next Steps

- In this 2-year R&TD effort, we have developed a closed-loop landing radar design and validation test-bed that integrates performance simulation with a hardware test-bed
- Preliminary validation of the simulation tool was completed in this effort
- The hardware test-bed has been tested in the lab, and an initial outdoor test was also completed
- Looking at funding opportunities to perform additional validation of the simulator and participate in a field campaign to demonstrate the hardware test-bed on an Octocopter or a small-scale rocket

Publications

- Karthik Srinivasan, Ninoslav Majurec, Razi Ahmed, Samuel Prager, Zahra Forootaninia, Peter, Mao, Shashank Joshil, Michael Tope, **“Terminal Descent Radar System Testbed for Future Planetary Landers,”** submitted to *IEEE Aerospace Conference,* Big Sky, Montana, 2021

References

- Gary S. Brown, “The Average Impulse Response of a Rough Surface and Its Applications," *IEEE Transactions of Antennas and Propagation,* **AP-25** (Jan, 199): pp. 67-74.
- Curtis W. Chen, “Approach for Modeling Coherent Radar Ground Echoes in Planetary Landing Simulations”, Journal of Spacecraft and Rockets, Vol. 55 (Jan, 2018).
- Brian D. Pollard an Curtis W. Chen, “A Radar Terminal Descent Sensor for the Mars Science Laboratory Mission”, IEEE Aerospace Conference, 2009
- Curtis W. Chen, Brian D. Pollard, “Radar Terminal Descent Sensor Performance During Mars Science Laboratory Landing”, Journal of Spacecraft and Rockets, Vol. 51 (July, 2014).