# The Propellant Refueling and On-orbit Transfer Experiment
## Flight results from the New Shepard P11 Mission

Kevin M. Crosby[1], Taylor Peterson[2], Alec Digirolamo[3], Dalton Callow[1]
[1]Carthage College; [2]University of Central Florida; [3]University of California – San Diego; Corresponding Author: Kevin Crosby (kcrosby@carthage.edu);

**Abstract**
We report flight test data for an implementation of a low-gravity liquid propellant mass gauging technology. The Propellant Refueling and On-orbit Transfer Operations (PROTO) payload experiment was flown on the Blue Origin New Shepard spacecraft and acquired mass gauging data before, during, and after, a tank drain and fill cycle that simulated an in-space propellant transfer event. The propellant simulant (water) was essentially quiescent in a gravitational field with accelerations of less than $10^{-5}$ g during the measurement. Propellant volume was estimated using the Modal Propellant Gauging (MPG) system with a measurement frequency of 1 Hz. We discuss the use of a cross-correlation algorithm to predict instantaneous zero-g propellant volumes from both a reference data set of 1-g (laboratory) data and a finite element model of 0-g modes.

**MPG Overview**
The MPG technology concept exploits the "added-mass" effect of liquid adhered to surfaces, such as the tank wall in a propellant system. Fluid, in contact with a structure, effectively increases the mass of the structure through the additional inertia required to move the fluid as the structure accelerates. This effect is evident in the commensurate reduction in the modal frequencies of the structure as compared to the unloaded surface. For liquid propellants in contact with tank walls, the added mass of the liquid can be large relative to the free-space mass of the tank wall and even thin layers of adhered liquid can measurably affect the resonant frequencies of the tank.

**The PROTO Payload Experiment**
The Propellant Refueling and On-orbit Transfer Operations experiment is a double-locker payload experiment designed for the New Shepard spacecraft. The payload, shown in Figure 1(a), consists of a 12-in diameter (OD) spherical experimental tank (the 'main' tank) outfitted with sponge and vane propellant management device. The main tank is connected to a receiver tank with a capacity of 2.8 liters, which sets the maximum transfer volume between the two tanks.

**Key Results**
The PROTO experiment flew on the New Shepard P11 mission and modal response of the tank during microgravity drain and fill operation was recorded and compared to modal response calculated within a coupled CFD-Finite Element model. The model makes predictions of modal response in zero-g for the tank at 1% liquid fill increments. Using the model predictions, measured modal response could predict the instantaneous fill volume of the tank to within 5% of the known volume throughout the drain sequence. Sample Frequency Response Functions for the flight and ground experiments are illustrated in Figure 1(b)

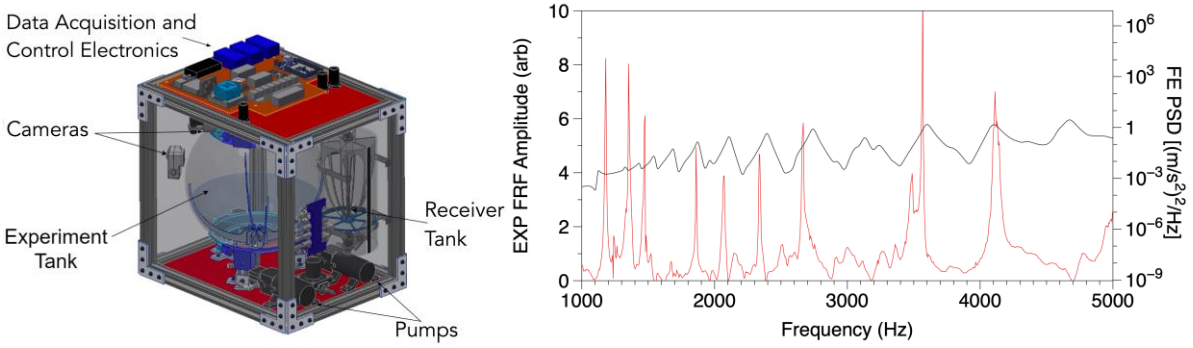


**Figure 1(a):** The PROTO Payload. (b) Modal response of empty PROTO tank (red) and FE model of the tank (black).