Yet More GNSS Applications: Volcanic Hail Detection and Instantaneous Velocities for Rapid Earthquake Characterization

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The Global Navigation Satellite System, which includes the GPS constellation, has evolved from its main purpose of positioning to the multi-tool of the Earth Sciences. Satellites broadcasting signals on at least two frequencies and a global network of high-quality, permanent ground receivers enable applications that span the determination of total electron content in the ionosphere, precipitable water content in the troposphere, landslide motion, tectonically induced deformation, strain release during earthquakes, magma reservoir changes, and mantle rheology. Recent high-rate (>= 1sps) and real-time networks allow us to infer kinematic slip models for large earthquakes, harden earthquake early warning applications, and develop tsunami and volcano warning applications. Analysis of the interference pattern between the direct and indirect signals, that arrive at the GNSS antenna indirectly via reflections from the environment, broadens the range of GNSS applications to soil moisture and vegetation analysis. An important third use of such reflection interference studies is the determination of antenna height changes above the reflecting surface. Processes that drive height changes include snow accumulation/melt, ocean tides, permafrost active layer dynamics.

Here, I present two specific, perhaps lesser-known applications. The first involves the detection and characterization of volcanic ash plumes, which disturb the GNSS signal travelling from satellites to ground receivers. Water-rich plumes refract and hence delay the signal, ash-rich plumes scatter the signal and hence lower the signal to noise ratio. For the 2014 Grimsvötn eruption in Iceland, we can combine the two techniques to track the high-altitude freezing of plume water to hail, an important mechanism to remove fine ash from the atmosphere.

The second application determines precise S wave ground velocities from single-station, single-frequency GNSS observations. In using subsequent carrier-phase observations we resolve the Doppler shift between satellite and receiver. Correcting for the satellite (even broadcast) orbit velocity allows us to retrieve the unsaturated ground receiver velocity, without needing to correct for atmospheric changes if high-rate data are used. The 2016 M7.1 Iniskin earthquake in Alaska provides an example where the GNSS peak-ground-velocity from such "low-grade" observations helps to refine the shake map as the GNSS sites fill gaps in the seismic network. This opens opportunities for tighter seismic and GNSS integrations in the future.

***(Left & Middle)** Azimuth elevation plot of phase noise along GNSS satellite tracks. Left shows the day before the 2011 Grimsvötn eruption, middle shows day of the eruption. Repeated noise for both days is marked. The eruptions are circled (red is from 19:00-20:00, gray 20:00-22:00) and we see clearly distinct noise. **(Right)** Shake map with GNSS peak-ground-velocities. Darker circles show where seismic-only ShakeMap underestimates GNSS observations, lighter circles show GNSS PGV are underestimated in the near field.*