**Thermospheric Stratospheric Seismic...**

returns. N- and U-shapes typically result from nonlinear propagation and caustic effects, which indicate...2014. The leftmost part of each trace, colored red, shows the seismic recording at ARCES which was used...15 Hukkakero explosions...SIGNALS RECORDED AT IS37...generated acoustic signals by Hukkakero blasts, recorded at other stations, have been considered in previous works, e.g. Gibbons...Modelling supports the hypothesis that these distinct parts of the wavetrain are stratospheric and mesospheric/thermospheric phases respectively. We observe that the trace velocity for almost all of the stratospheric part of the wavetrain is essentially constant, whereas the thermospheric phases are associated with quite differing trace velocities: indicative of turning points at different altitudes.

The final three explosions at Hukkakero in 2014 were of far lower yield and only generated signal detections at IS37 in the stratospheric part of the wavetrain. In this study we make attempts to interpret features of the observed wavetrains, like the trace velocities and celerities, through modelling in perturbed atmospheric models. One goal for this study is to be able to create so-called celerity expectation lookup tables applicable for use in event location algorithms.

**HUKKAKERO GROUND TRUTH EVENTS IN 2014**

Between August 22 and September 3 in 2014, the Finnish military set off 15 explosions to demolish ammunition at the Hukkakero site in Northern Finland. These generated seismic signals which were used to locate and time the events; see event list below. Acoustic signals generated by Hukkakero blasts, recorded at other stations, have been considered in previous works, e.g. Gibbons et al. (2007, 2015).

**CONSTRUCTION OF ATMOSPHERIC MODELS FOR RAY-TRACING**

Using a philosophy akin to the one underlying the Ground-to-Space (G2S) model (Drob et al., 2010), we use openly available sources for three altitude regions to setup a compound model of the atmospheric wind and temperature:

- For altitudes above 60 km, the most recent version of the Naval Research Laboratory (NRL) empirical Horizontal Wind Model (HWM) is applied while the temperature is extracted from the NRLMSE-00 climatology.
- For altitudes between 25 and 70 km, we use the NASA Modern-Era Retrospective Analysis (MERRA) both for winds and temperature.
- For the lowest altitudes, up to 35 km, we apply the NCEP / NCAR reanalysis. In the overlap altitude regions we apply a Hmun-weighted average. For temporal and spatial coordinates where the underlying models are not available, we use multi-dimensional linear interpolation between the nearest gridpoints.

**INTRODUCING ATMOSPHERIC WIND PERTURBATIONS DUE TO GRAVITY WAVES**

Following the approach of Gibson et al. (2008), we generate Gardner wave spectra at 4 different altitudes. Each spectrum is then multiplied by a random phase factor and inverse Fourier transformed. Finally, altitude horizontal wave-gravity profiles are formed by weighted averaging over the realizations corresponding to the 4 underlying altitudes.

By varying the Gardner spectrum power, we can vary the amplitude of the wind perturbations.

**MODELLING IN UNPERTURBED MODELS**

For each of the 12 largest Hukkakero explosions:

- Calculate celerities of observed coherent high-frequency (HF, 1-6 Hz) and low-frequency (LF, below 1 Hz) energy originating from the explosions.
- Calculate celerities of signals modelled using the atmospheric model at the time of the event.
- Calculate probabilities for detection both for observed and for modelled celerities.

The figure to the right shows rays modelled (Walker 2012) in the atmospheric model at the time of the event on 24 August 2014. The figure to the right compares the observed and modelled celerities for each event, as well as ensemble probabilities.

The other colors represent modelled returns, with the color scale on top of the figure indicating the maximum turning altitude of the ray.

**SUMMARY**

We look at the “full wavetrain celerity” and compare recorded detections to modelled detections. The atmospheric wind models are perturbed using gravity waves.

For stratospheric and mesospheric arrivals, the amplitude of the Gibson gravity-wave spectra are quite appropriate, however for the thermospheric arrivals no perturbations are needed to model the recorded signals.

However, we need to emphasize the ray-tracing method’s shortcomings due to its inherent high-frequency assumption, which for example can result in overestimating the width of shadow zones. By varying the energy of the Gibson spectra and then shooting rays through a large set of corresponding pertur-