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Probabilistic meteor analysis and the first head echo results from the PANSY radar

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Abstract

We have a long-term research goal of creating a reliable loop between radar measurements and simulations of meteor events. This loop stretches all the way from the origin of meteoroids in the solar system to raw voltage data in a radar system. Focusing on the radar measurements, we are currently upgrading our meteor head echo analysis pipeline, expanding our analysis capabilities to trail echos and validating measurements. We present the recent upgrades to the MU radar analysis resulting in a new database, the first steps towards improved meteor trail echo analysis and the first results from meteor head echo measurements with the PANSY radar.

1 Introduction

We have a long-term research goal of creating a reliable loop between radar measurements and simulations of meteor events. This loop stretches all the way from the origin of meteoroids in the solar system to raw voltage data in a radar system. As a part of this goal we need to address the reliability of meteor event databases and the breadth of available data. To achieve this goal two factors have been considered: analysis validity and result uncertainty.

Starting with analysis validity and considering antenna array radars that use interferometry to determine the meteoroid trajectory, the weakest link in the analysis is often the direction of arrival (DOA) determination. The DOA determination is weaker than both range and line of sight velocity, as the latter are calculated from the coherent or incoherent integration of the radar systems channels while DOA determination utilizes the separate signals in each channel. Additionally, signal strength and antenna placement dependant angular ambiguities arise for most commonly used radar antenna arrays [1]. For this reason, we have developed and performed Direct Monte-Carlo (DMC) simulations of noisy simulated DOA determinations to classify when data is reliable. These simulations enable us to determine output probability distributions for given input signals and noise models. Thus, extending the DMC simulation to include the entire pipeline allows us to directly address the second factor: result uncertainty. Previously, the meteoroid trajectory was fitted using a least squares method using the measurements. We have significantly improved the meteoroid trajectory fitting process by using the DMC simulations, together with some strong assumptions, to find the probability distribution of each measurement. When the probability distribution of each measurement point is available, a Bayesian inference approach to trajectory fitting can be adopted to also find the probability distribution of possible trajectories. We have applied a Markov Chain Monte Carlo (MCMC) method to sample the posterior distribution over possible meteoroid trajectories. This allows each detected meteor head echo to have an associated probability distribution for the trajectory, the orbit, the time series, and all other relevant parameters.

The 46.5 MHz Middle and Upper atmosphere (MU) radar near Shigaraki, Japan (34.85°N, 136.10°E) has a nominal peak transmitter power of 1 MW and a maximum beam duty cycle of 5%. The meteor head echo data was collected using the experimental setup described in [2], utilizing all 25 channels of the digital receiver system. The output of each digital channel is the sum of the received radio signal from a subgroup of 19 Yagi antennas. The whole array consists of 475 antennas, evenly distributed in a 103 m circular aperture, with a main lobe maximum gain of 34 dB and a minimum half power beam width of 3.6°.

While updating the analysis software, we also aim to expand the amount of meteor data to trail echo radars and have begun efforts improving the available data in our nearby trail echo radar infrastructure. More specifically, the common SKiYMET radars [3] that are scattered across the world currently have angular ambiguity problems [1] and about 10-30% of the data is affected. However, as trail echoes are virtually stationary compared to head echoes, temporal integration techniques can be applied to resolve these issues. We present our efforts into applying such techniques to the radars in our region. Finally, also in an effort to expand the amount of available meteor data, we have been conducting meteor head echo experiments at the PANSY radar system, located at Syowa Station in the Antarctic [4].

The first subarrays of the PANSY radar was installed in 2011. The first continuous observations of polar mesospheric summer echoes were made with one subarray of 19

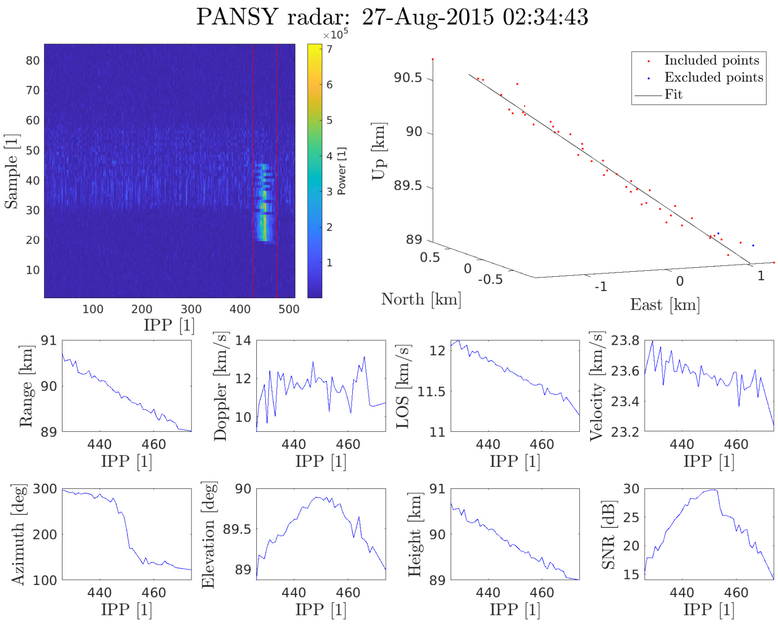

Figure 1. Example of a meteor head echo measured using the PANSY radar. Here, "LOS" is the line of sight velocity component while "Velocity" is the actual meteoroid velocity. The interpulse period (IPP) was 3.12 *ms*. The upper left panel is a range-time-signal plot where "Sample" indicates temporal samples received from each transmitted radar pulse. Using the speed of light, the vertical axis translates to range at 0.9 km discrete intervals as the integration time per sample was 6 *ms*. The meteor echo delimited inside red vertical bars contains the returns from 26 samples long transmitted coded sequences.

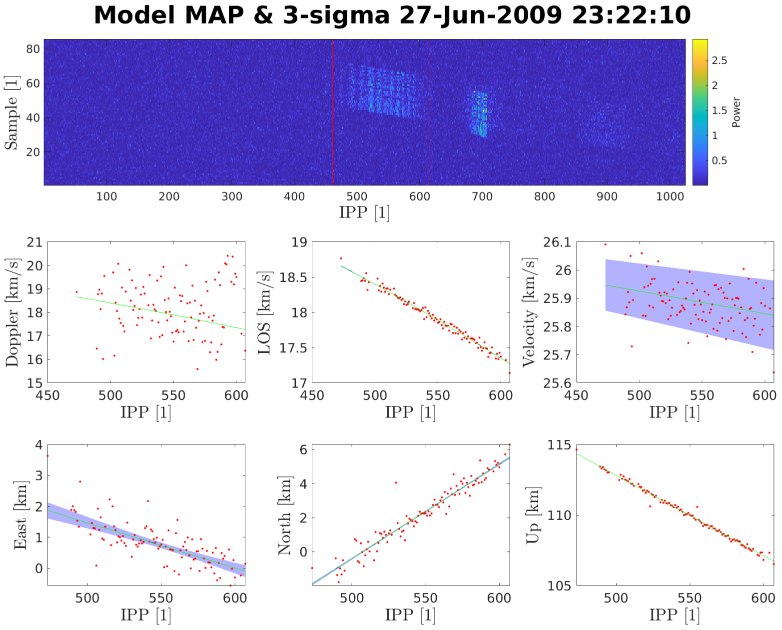

Figure 2. Example of fitting a trajectory model to MU radar meteor head echo data. Here, the model is fitted using the Markov Chain Monte Carlo (MCMC) method. The maximum a posteriori probability (MAP) model is shown as green solid lines and the 3s equivalent partitions are shown as shaded blue regions. The upper panel range-time-signal plot has the same structure as in Fig. 1.

antennas in January-February 2012. Due to snow accumulation in the originally symmetric antenna field consisting of 1045 crossed Yagi antennas summed into 55 channels, several of the subarrays were moved to higher ground, thus forming an asymmetric antenna field [4]. The PANSY operating frequency is centred at 47 MHz and it has a peak transmitter power of 500 kW. The radar is a challenge for DOA determinations as the subgroups are partially disjoint and located at different altitudes. Even within subgroups, antennas are elevated non-symmetrically. Furthermore, antennas are sometimes moved or intermittently disconnected from the system depending on snow accumulation conditions. However, the DOA ambiguity analysis, DMC simulations and raw data simulations has given enough insight to implement a version of the MU radar analysis pipeline. The simulations also showed that the radar is expected to be exceptional at interferometry [1], and as such PANSY observations contribute to the long-term goal of data breadth by adding a high-accuracy source of meteor head echo data at the high-latitude southern hemisphere.

2 Examples

We present the methodology of the probabilistic meteor analysis and general characteristics of the resulting database and its scientific uses. Additionally, we present the first meteor head echo analysis results from the PANSY radar. An example of a meteor head echo event that has been automatically detected and analysed is illustrated in Fig. 1.

An example of a trajectory fitting is illustrated in Fig. 2 for an event measured by the MU radar. The pipeline supports fitting for arbitrary motion models. In the examples we have used a linear motion exponential velocity model. This model is based on eight parameters: three coordinates for trajectory start position, two angles for the velocity radiant, and three parameters for the exponential velocity model $v(t) = a - be^{-tc}$. As the analysis is probabilistic, every data point has an associated probability distribution. This allows us to fit models using Bayes theorem to calculate the posterior distribution. The most probable model is given by the maximum a posteriori probability (MAP) and how uncertain we are of the model parameters is given by the morphology of the posterior. However, as the posterior is generally not calculable analytically we sample it using the MCMC method. In Fig. 3 we illustrate the MCMC samples of the posterior for the example in Fig. 2.

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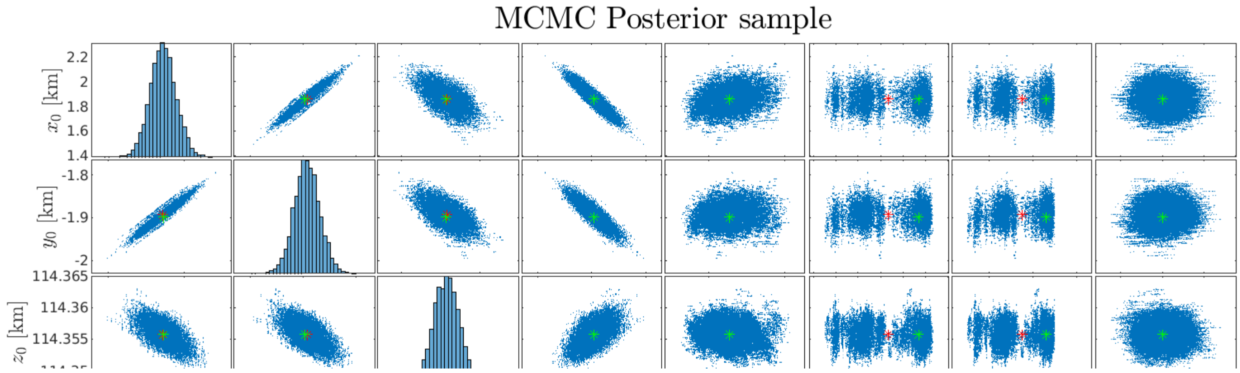

Figure 3. The Markov Chain Monte Carlo (MCMC) samples used to calculate the maximum a posteriori probability (MAP) and the 3s equivalent partitions in Fig. 2. A note for the experienced statistician: we are clearly not achieving good sample mixing in the $a; b$ parameter space of the exponential velocity model $v(t) = a - be^{-tc}$. This is caused by these parameters being correlated given the observations and current implementation (i.e there is no difference between "high velocity with already decelerated velocity at $t = 0$" and "low velocity and no deceleration at $t = 0$"). We plan to implement and apply arbitrary transforms to parameters before and after sampling and parameter restrictions trough priors to improve the mixing.