

Methods for Correcting the Group Index of Refraction at the PPM Level for Outdoor Electronic Distance Measurements

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The Green Bank Telescope (GBT)¹ is a recently completed 100-meter radio telescope built by the National Radio Astronomy Observatory in Green Bank, WV. The GBT incorporates a first-of-its-kind active surface and precision-pointing system based on a custom designed system of 18 automated electronic distance measurement (EDM) instruments. Twelve EDMs are mounted on stable monuments equally spaced on a 120-meter radius around the telescope. These ground-based instruments measure cardinal points on the structure to correct for thermal and gravitational deflections in the structure and thus correct the pointing with respect to the stable earth reference. Six additional instruments mounted on the deflecting structure measure the surface of the main reflector and generate corrections which are used to move 2209 actuators to correct the shape of the main reflector. By tying the 12 stable ground instrument measurements to the 6 structurally mounted instruments, they are referenced to the same coordinate system and thus the absolute pointing of the reflector is determined. The system can best be described as a large *in situ* coordinate measurement machine working in a 240-meter diameter X 150-meter high cylindrical volume (6 million cubic meters). The desired accuracy is of the order of 1 part per million (ppm) (0.100 mm at 100 meters). Due to the nature of the application, the EDMs must operate under outdoor ambient conditions.

The instrument is based on a phase measurement of a 1.5 GHz modulated laser, and therefore the phase of the 1.5 GHz return beam depends on the speed of light - more specifically, the group index of refraction for the modulated beam. To first order, the group index of refraction depends on the temperature, humidity, and pressure integrated through the path. For outdoor measurements, temperature is the primary limitation to the accuracy of EDM instruments. The group index of refraction changes by about 1 ppm/degree C - our entire error budget. The group index of refraction as a function of temperature, humidity, and pressure, has been worked out to about 0.001 ppm. The problem is that the temperature is not uniform throughout the volume. For example, the temperature near the ground can vary significantly from the temperature 150 meters higher at the top of the telescope. The 100-meter reflector cast a large shadow, which produces radical gradients in the temperature profile. Temperature profiles across the reflector surface depend on shadows and angle of the sun. Melting snow, standing water, ground cover, etc. can produce large gradients in the water vapor pressure. Clearly, a simple measurement of temperature, humidity, and pressure is insufficient to model the group index of refraction at the 1-ppm level throughout the volume.

The GBT system does have some advantage over general surveying problems. Unlike a general surveying problem where one is working from temporary tripods and limited bench marks, the 12 ground-based monuments were built to be very stable and can be used as bench marks, and up to 60 bi-directional base-lines can be constructed. Due to the automated control system and speed of the measurements (5 points/second), vast amounts of data can be generated and used in a model. The geometry of the base-lines can be measured under ideal conditions, and the base-lines can be used as ambient refractometers to measure the group index of refraction directly. A

fixed retroreflector on an adjacent mountain can be used as a macro refractometer. Temperature, humidity, and pressure can be measured at a number of locations. Acoustic thermometry is also an option. Experimental data will be presented which puts bounds on the accuracy of the model under various weather conditions.