

Mach-Number Measurement with Laser and Pressure Probes in Humid Supersonic Flow

G. C. Herring

NASA Langley Research Center, M/S 493
Hampton, VA 23681-2199

Abstract

Mach-number measurements using a nonintrusive optical technique, laser-induced thermal acoustics (LITA), are compared to pressure probes in humid supersonic airflow. The two techniques agree well in dry flow (-35 °C dew point), but LITA measurements show about five times larger fractional change in Mach number than that of the pressure-probe when water is purposefully introduced into the flow. Possible reasons for this discrepancy are discussed.

Key words: Laser-induced thermal acoustics (LITA), Pressure probe, Mach number
measurement in humid supersonic air

Laser-based vapor screen [1] is commonly used for flow visualization in some high-speed wind tunnels, including NASA Langley Research Center's (LaRC) Unitary Plan Wind Tunnel (UPWT) [2]. Vapor screen visualization is accomplished by adding water to the wind tunnel circuit; the cooled supersonic flow condenses the H_2O vapor into small H_2O droplets or ice crystals. Flow visualization is possible by illumination of the H_2O particles with a laser light sheet. However, adding H_2O to a supersonic wind tunnel alters the flow conditions in the test section compared to otherwise identical, but dry conditions. Hence, typical aeronautical testing with pressure probes is done under dry tunnel conditions. Some flow facilities have measured and specified the effect of flow humidity on tunnel Mach number (e.g., see pp. 87 of Ref. 2), so that flow visualization users will know the effect of high humidity.

Another optical technique, laser-induced thermal acoustics (LITA), has been recently demonstrated for Mach number measurement in a supersonic flow. No seeding is required with this approach. LITA-based, nonintrusive, time-averaged and simultaneous measurements of Mach number, static temperature, and static pressure at a localized point in the free-stream flow of UPWT are demonstrated and described in Ref. 3. The present note describes a novel comparative study of pressure probe and LITA-based Mach number measurements versus humidity in the UPWT.

A more-detailed description of LITA velocimetry at LaRC can be found for supersonic [3], transonic [4], and subsonic [5] flows, while the work of other groups is summarized in a recent review [6]. LITA is a laser diagnostic that typically measures sound speed and one directional component of Mach number simultaneously in a flow

volume defined by crossed laser beams. If the flow composition is known, then translational temperature can be derived from the sound speed, and gas pressure is measurable under certain restricted circumstances [3, 7].

In LITA, two focused and crossed 1.06- μm laser beams from a Q-switched Nd:YAG (150 mJ / pulse / beam) induce two counter-propagating sound-wave packets in the sample volume defined by the crossing region. These sound waves constitute gas-density gratings in the fluid. The ~ 100 dB (re 20 μPa) sound pressure level corresponds to a fractional density change of $\sim 10^{-4}$. Thus the technique can be characterized as nonintrusive. Flow velocity and sound speed are determined from distinct Doppler shifts of Bragg-scattered light from a third laser beam (probe at 532-nm) that intercepts the sound wave packets. The sound packets reflect a tiny fraction of the incident probe intensity to a detector positioned at the Bragg-scattering angle. All LITA measurements presented here are time averaged over 17 sec (500 laser pulses at rate 30 Hz).

Free-stream results comparing measurements of Mach number M by a pressure probe and LITA are given in Ref. 3 for dry airflow (dew point = -35 $^{\circ}\text{C}$) at Reynolds number $R = 6 \times 10^4/\text{m}$. Fig. 1 summarizes some of those results and shows exceedingly good agreement (typical differences of Mach 0.003) between time-averaged measurements from both techniques, for the Mach range 1.6-2.2. Open circles are from one day of testing, the solid triangle is from a second day, and the solid line represents perfect agreement between the two techniques.

Results comparing the two Mach number measurements versus steady-state water content are given in Fig. 2, at approximately Mach 2. Pressure-probe results are from Fig. 27, pp. 87, of Ref. 2, and the LITA results were obtained during the work of Ref. 3.

Pressure-probe results were obtained at Mach 2.17, while LITA results were obtained at Mach 1.97. This is the closest Mach-number match that is possible for the limited humidity studies from the two unrelated works of Refs. 2 and 3. Results at other Mach numbers, illustrated on page 87 of Ref. 2, suggest that one expects only a small change in the effect of adding water between these two slightly different Mach numbers. Thus it appears reasonable to compare these two data sets.

Pressure-probe results are plotted using the right-hand Mach-number scale, while LITA results use the left-hand Mach scale. Offsetting the two scales by Mach 0.2 provides a simple normalized comparison of the relative change in Mach number at the two slightly different Mach numbers. Horizontal lines provide a convenient reference for the eye. Open squares are probe results at $R = 6 \times 10^4/\text{m}$, open diamonds are probe values at $R = 12 \times 10^4/\text{m}$, and solid triangles are LITA results at $R = 6 \times 10^4/\text{m}$. The left-most triangle is the same lone triangle plotted in Fig. 1. The abscissa gives the dew point of the airflow. A dew point of $-12\text{ }^\circ\text{C}$ corresponds to a water concentration of 0.5% at the stagnation conditions 70 kPa (0.7 atm) and $52\text{ }^\circ\text{C}$. As water concentration in the flow is increased, the difference between the two methods increases for the change in Mach number, illustrating a potential error in one or both techniques. LITA measures a factor of five larger change in Mach number due to the addition of water, as the humidity varies from the driest dew point of $-35\text{ }^\circ\text{C}$ ($-30\text{ }^\circ\text{F}$) to $-12\text{ }^\circ\text{C}$ ($+11\text{ }^\circ\text{F}$). Along with the decrease in Mach number, LITA also measures the free-stream static temperature T to increase (data omitted for brevity) from $-93\text{ }^\circ\text{C}$ to $-86\text{ }^\circ\text{C}$ as dew point varies from $-35\text{ }^\circ\text{C}$ to $-12\text{ }^\circ\text{C}$. This temperature increase and Mach number decrease come from the heat release during water vapor condensation into particles.

Uncertainties in the LITA data [3] are typically $\leq 0.2\%$, or $\Delta M = \pm 0.004$.

Uncertainties in the pressure-probe data are not quoted in Ref. 2, but the precision is estimated to be $\Delta M = \pm 0.005$ from the point-to-point variation from an imaginary smooth curve through the probe data. Thus the difference in ΔM (a factor of five) for the two measurement techniques, at $-12\text{ }^{\circ}\text{C}$, exceeds the estimated combined uncertainty of $\Delta M \approx \pm 0.009$ of both measurements. The good agreement of the two methods in Fig. 1 is typical of many comparisons of LITA and traditional methods, performed at LaRC over one decade, so the disagreement of Fig. 2 is surprising.

One potential reason for the discrepancy is an error in the LITA measurement due to a change in molecular mass μ from adding water vapor to air. The highest humidity in Fig. 2 is equivalent to $\approx 2\%$ water vapor before supersonic expansion. Adding this H_2O would reduce the average molecular mass by only 1% and increase the sound speed V_s by 0.5% ($V_s^2 \propto T / \mu$). Furthermore, most water vapor is condensed into particles in the expansion to Mach 2 and is not in vapor phase in the test section. The error in measured M is likely $\ll 0.5\%$ and negligible.

In the dry airflow of Fig. 1, LITA generates only acoustic gratings from a purely electrostrictive effect. Solid, liquid and vapor phases of water have weak absorptions at the pump-laser wavelength of 1064 nm. Gas heating after an optical absorption leads to a second possible error in the humid LITA measurements of Fig. 2: a LITA-generated thermal-based grating in gas density. In fact, in humid flow, we do observe that LITA generates a weak thermal grating (in addition to the acoustic grating). The thermal grating increases in strength as the humidity increases. At $-12\text{ }^{\circ}\text{C}$, the thermal-grating signal was about equal to the acoustic-grating signal. An absorption coefficient of $\sim 10^{-4}$

cm^{-1} is inferred by an estimated (not measured) thermal grating reflectivity of $\sim 10^{-9}$. The absorbed energy is more than enough to heat the gas by 7 °C and reduce M from 1.96 to 1.91, if it is assumed that all absorbed energy were to be transferred to the gas (e.g., by vaporization of the ice particles). If the crystals do not vaporize and only a small fraction of the energy absorbed by the crystals is transferred to the gas in the LITA observation time of 1 μsec , the thermal grating is unlikely to account for the Mach number discrepancy. The estimated laser peak intensity of 10^{11} W/cm^2 and our observation of rare laser-induced breakdown (once every 1000 laser pulses) suggest that a majority of the water particles survive the laser pulse [8]. Although this potential error should not be ruled out yet, the best evidence for asserting that it is negligible is that the strength of the thermal grating is about the same as the strength of the acoustic grating, which is known [9] to exhibit fractional changes in gas density and temperature of $\sim 10^{-4}$.

A third explanation for the difference of Fig. 2 is an error in the pressure probe measurement, related to the particle laden free-stream. As particles transit the shock from the pressure probe, they are heated. Immediate (or delayed) evaporation of these H_2O particles, directly behind the probe shock (or in the probe duct), would anomalously alter the flow conditions sampled by the probe. In this scenario, the disagreement in humid flow is speculatively attributed to the probe because of the heating and evaporation of the water particles that are entrained in the cold free-stream flow. Two different estimates of the probe error can be made. First, the energy available to heat the gas (if all H_2O in the flow condenses into crystals in the nozzle expansion and then all particles vaporize as they cross the probe shock) is given by the heats of fusion and vaporization. This estimate gives $\Delta T \sim 8 \text{ °C}$ for 0.5% fractional water vapor, more

consistent with the LITA measurement of $\Delta T \approx 7^\circ\text{C}$ than the inferred probe measurement of $\Delta T \sim 1^\circ\text{C}$. This inferred ΔT from the probe was estimated using isentropic expansion tables to convert ΔM to ΔT . Second, with the same assumptions, ideal 1-dimensional flow with heat addition [10] predicts $\Delta M \sim 0.09$, more consistent with LITA's measurement of $\Delta M \approx 0.05$ than the probe measurement of $\Delta M \approx 0.01$.

In summary, pressure probe and noninvasive LITA-based Mach-number data were compared and found to disagree in humid supersonic airflow, although they agree well in dry flow. Additional work would be useful to unambiguously determine whether the difference in the two methods is due to the LITA or probe method.

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Figure Captions

1. Probe and LITA-based Mach-number for dry air (dew point = -35 °C).
2. Probe and LITA-based Mach-number versus water concentration.

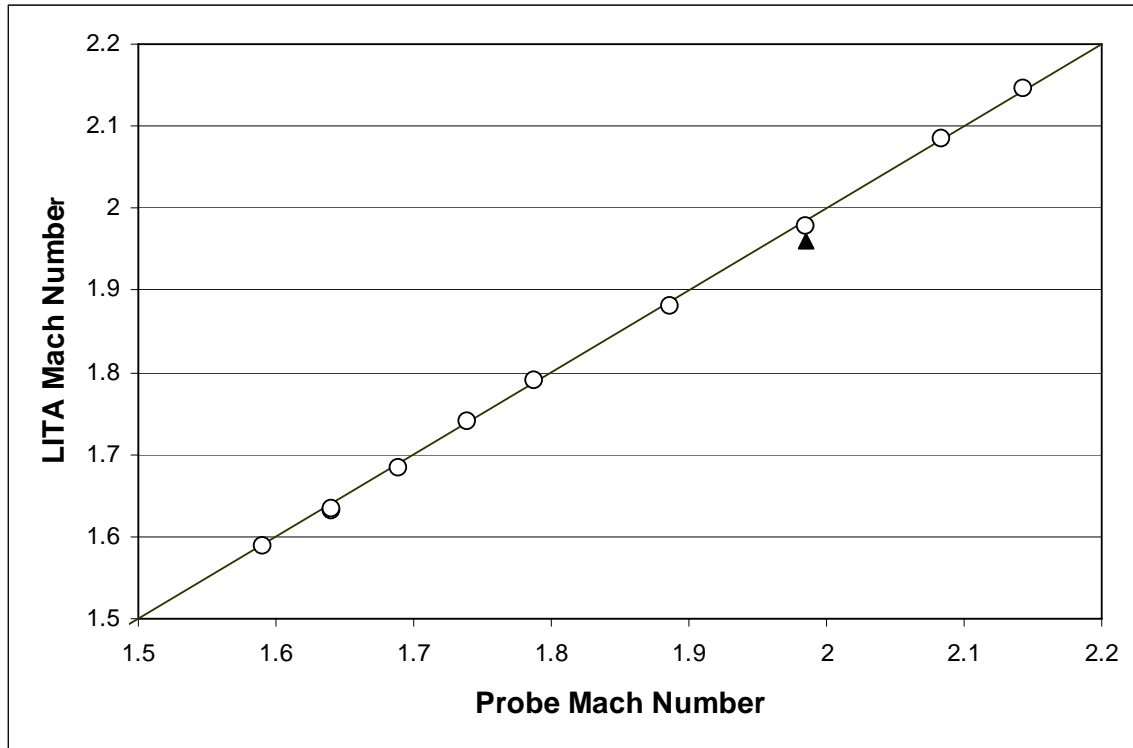


Figure 1

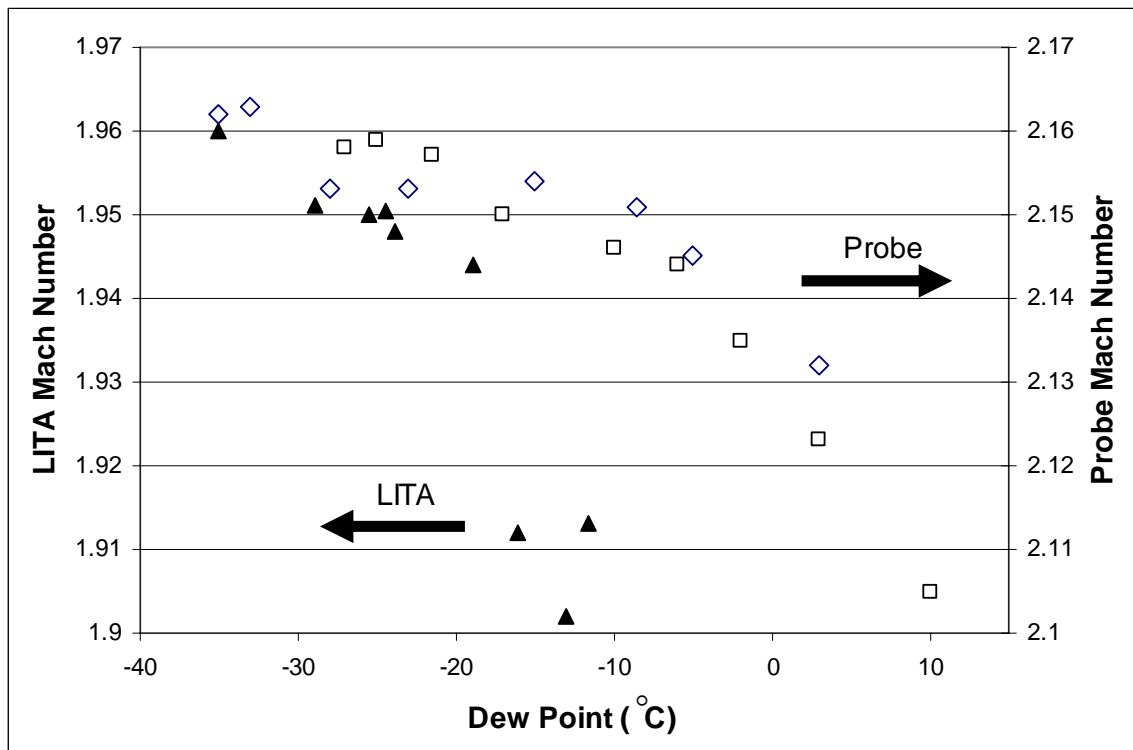


Figure 2