Calibrating {p, q, T} Using LAMS

A[illegible]er

RAF Algorithm Review

December 2 2011

ROADMAP

Steps:

1. $p_t = p + q$ is accurate

p_t

- p_t=total pressure, p=static, q =dynamic
- pitot tube insensitive to flow angle (<0.1%)
- orientation removes normal offset
- redundant measurements ⇒consistency
- still, AN ASSUMPTION

ROADMAP

Steps:

1. $p_t = p + q$ is accurate
2. Errors in p and q arise from error at static sources

Consequences

- p and q are the measured quantities
- plumbing: q is difference, $q = p_t - p$
- therefore $\Delta p = -\Delta q$
- can predict q from LAMS, hence Δq
- can use Δp to correct p

ROADMAP

Steps:

1. $p_t = p + q$ is accurate
2. Errors in p and q arise from error at static sources
3. Find Δq required to match LAMS; hence Δp

What q is required to match LAMS?

- TAS: depends on q, p, T
- relatively insensitive to T (iterate...)
- find Δq s.th. $q_m + \Delta q$, $p_m - \Delta q$, T gives v_{LAMS}

ROADMAP

Steps:

1. $p_t = p + q$ is accurate
2. Errors in p and q arise from error at static sources
3. Find Δq required to match LAMS; hence Δp
4. Refinements for accuracy

Adjustments

- correct because p enters the prediction of Δp
- calculate humidity influences on R_a, C_p, C_v, $\gamma = c_p/c_v$
- correct for offset angle of LAMS
- recalculate T using corrected pressures

ROADMAP

Steps:

1. $p_t = p + q$ is accurate
2. Errors in p and q arise from error at static sources
3. Find Δq required to match LAMS; hence Δp
4. Refinements for accuracy
5. Δp is a function of measured quantities like p_m, q_m, α_m

Fit Correction to p and q given by LAMS:

- use second-by-second prediction of Δq from LAMS
- try fits like $(\Delta p/p) = a_0 + a_1 q + a_2 (ADIFR/QCR)$
- find $\Delta p(measurements)$

ROADMAP

Steps:

1. $p_t = p + q$ is accurate
2. Errors in p and q arise from error at static sources
3. Find Δq required to match LAMS; hence Δp
4. Refinements for accuracy
5. Δp is a function of measured quantities like p_m, q_m, α_m
6. Test using flight maneuvers, also calibrating T

Maneuvers for testing results

- reverse-heading maneuvers
- climbs and descents to calibrate temperature via integration of the hydrostatic equation

ROADMAP

Steps:

1. $p_t = p + q$ is accurate
2. Errors in p and q arise from error at static sources
3. Find Δq required to match LAMS; hence Δp
4. Refinements for accuracy
5. Δp is a function of measured quantities like p_m, q_m, α_m
6. Test using flight maneuvers, also calibrating T
7. Use LAMS with the above results to measure T directly.

LAMS-based measurement of temperature

- LAMS provides TAS=v
- p and q determine Mach number $M = v/v_s$
- $v_s = \sqrt{\gamma R_a T}$ so measured M and $v \Rightarrow T$ without reference to a temperature sensor

ROADMAP

Steps:

1. $p_t = p + q$ is accurate
2. Errors in p and q arise from error at static sources
3. Find Δq required to match LAMS; hence Δp
4. Refinements for accuracy
5. Δp is a function of measured quantities like p_m, q_m, α_m
6. Test using flight maneuvers, also calibrating T
7. Use LAMS with the above results to measure T directly.

Results:

1. Calibration of dynamic pressure, hence true airspeed, hence longitudinal component of wind

ROADMAP

Steps:

1. $p_t = p + q$ is accurate
2. Errors in p and q arise from error at static sources
3. Find Δq required to match LAMS; hence Δp
4. Refinements for accuracy
5. Δp is a function of measured quantities like p_m, q_m, α_m
6. Test using flight maneuvers, also calibrating T
7. Use LAMS with the above results to measure T directly.

Results:

1. Calibration of dynamic pressure, hence true airspeed, hence longitudinal component of wind
2. Calibration of pressure

ROADMAP

Steps:

1. $p_t = p + q$ is accurate
2. Errors in p and q arise from error at static sources
3. Find Δq required to match LAMS; hence Δp
4. Refinements for accuracy
5. Δp is a function of measured quantities like p_m, q_m, α_m
6. Test using flight maneuvers, also calibrating T
7. Use LAMS with the above results to measure T directly.

Results:

1. Calibration of dynamic pressure, hence true airspeed, hence longitudinal component of wind
2. Calibration of pressure
3. Calibration of temperature via accurate measurements of pressure + GPS

ROADMAP

Steps:

1. $p_t = p + q$ is accurate
2. Errors in p and q arise from error at static sources
3. Find Δq required to match LAMS; hence Δp
4. Refinements for accuracy
5. Δp is a function of measured quantities like p_m, q_m, α_m
6. Test using flight maneuvers, also calibrating T
7. Use LAMS with the above results to measure T directly.

Results:

1. Calibration of dynamic pressure, hence true airspeed, hence longitudinal component of wind
2. Calibration of pressure
3. Calibration of temperature via accurate measurements of pressure + GPS
4. Provide new independent temperature measurement that *should* work in cloud

THE MEASUREMENT OF TOTAL PRESSURE

Basic Measurements

static pressure PSFD, PSFRD

- absolute sensors
- ± 0.1 mb (Parascientific Model 1000)

dynamic pressure QCF, QCRF

- differential sensors, total vs static
- ± 0.05 mb

hypothesis:

$p_t = p + q$ is accurate

THE MEASUREMENT OF TOTAL PRESSURE

Basic Measurements

static pressure PSFD, PSFRD

- absolute sensors
- $\pm$0.1 mb (Parascientific Model 1000)

dynamic pressure QCF, QCRF

- differential sensors, total vs static
- $\pm$0.05 mb

hypothesis:

$p_t = p + q$ is accurate

pitot tube performance

- typical sensitivity <1% at angles up to 10°, 0.2% up to 5°.
- mean orientation chosen along expected flow direction, not centerline

THE MEASUREMENT OF TOTAL PRESSURE

Basic Measurements

static pressure PSFD, PSFRD

- absolute sensors
- ± 0.1 mb (Parascientific Model 1000)

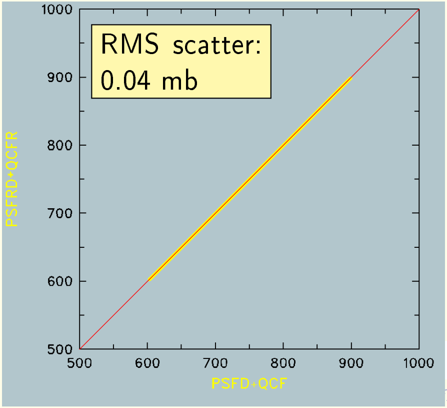
dynamic pressure QCF, QCRF

- differential sensors, total vs static
- ± 0.05 mb

hypothesis:

$p_t = p + q$ is accurate

$$\text{PSFRD+QCFR} = a_1(\text{PSFD+QCF}) + a_2$$
$$a_1 = 1.0000,\ a_2 = 0.10 \text{ mb}$$



THE EQUATIONS

Energy conservation in compressible flow: $\frac{v^2}{2} + c_p T = \text{constant}$
For adiabatic compression to stagnation $(v = 0)$,

$$M^2 = \frac{v^2}{\gamma R_a T} = \left\{ \left(\frac{2c_v}{R_d} \right) \left[\left(\frac{p+q}{p} \right)^{R_a/c_p} - 1 \right] \right\}$$

$$q = p \left\{ \left(\frac{v^2}{2c_p T} + 1 \right)^{c_p/R_a} - 1 \right\} = p\chi$$

where the last equality defines $\chi(v, T)$. Write in terms of measured quantities $p_m = p - \Delta p$ and $q_m = q - \Delta q$ and unknown $\Delta p = -\Delta q$:

$$\boxed{\Delta p = \frac{q_m - p_m \chi}{1 + \chi}}$$

HOW TO ADDRESS NEED FOR TEMPERATURE

Need Temperature:

Have v from LAMS

$$\chi(v,T)=\left\{\left(\frac{v^2}{2c_pT}+1\right)^{c_p/R_a}-1\right\}$$

- Not very sensitive: Fractional error in T is small
- Use available-processed T as the first approximation
- Then, iterate both in calculation and in calibration

Determining "PCORR" Function

$$\boxed{\Delta p=\frac{q_m-p_m\chi}{1+\chi}}$$

- Airspeed from LAMS gives second-by-second estimates of Δp
- Can fit those values to get Δp as function of other measurements

REFINEMENTS FOR ACCURACY

Moist Air Corrections

- humidity matters at this level of precision
- Use R_a, c_p, γ adjusted for humidity

Pointing Angle Corrections

- $v_l = v\cos(\theta)$ where v_l is the speed measured by LAMS
- $\cos\theta \simeq \cos(\theta_1+\alpha)\cos(\theta_2-\beta)$
    - θ_1 is the pointing angle above the longitudinal axis=0.1°
    - θ_2 is the pointing angle to starboard of the longitudinal axis=-0.2°
    - if $\alpha = -4^\circ$,$\cos\theta \simeq 0.9976$ and at 130 m/s $\delta v = 0.3$ m/s.
- Therefore, use $v = v_l/\cos(\theta)$ in the preceding equation

FITS TO Δp

Candidate Fit Parameters

1. p: Effects on Δp probably scale with pressure, so fitting functions of the form $\frac{\Delta p}{p} = f(\ldots)$ seems appropriate and provided improved fits
2. q or q/p
3. α or ADIFR/QCR
4. β or BDIFR/QCR
5. M (but M^2 represents much of the same dependence as q/p)

PREFERRED FIT

Best Option?

$$\frac{\Delta p}{\mathrm{PSFD}} = a_0 + a_1 \frac{\mathrm{ADIFR}}{\mathrm{QCR}} + a_2 \frac{\mathrm{QCF}}{\mathrm{PSFD}}$$

Fit procedure:

1. Determine a_1 by fit to pitch maneuvers
2. Keep a_1 constant and fit for a_0 and a_2 using data from all times when LAMS provides a measurement of v.
3. Obtain coefficients by separate fits for {PSFD, QCF} and {PSFRD, QCFR}

RMS error vs LAMS measurements: 0.3 mb, 1-Hz measurements.

- (Different sample volumes)
- Mean correction: uncertainty < 0.01 mb (>10,000 measurements)

FIT THAT IS BEST FOR MANEUVERS

Another Good Option

$$\frac{\Delta p}{\mathrm{PSFD}} = b_0 + b_1 \frac{\mathrm{ADIFR}}{\mathrm{QCR}} + b_2 \mathrm{XMACH2} + b_3 \frac{\mathrm{BDIFR}}{\mathrm{QCR}}$$

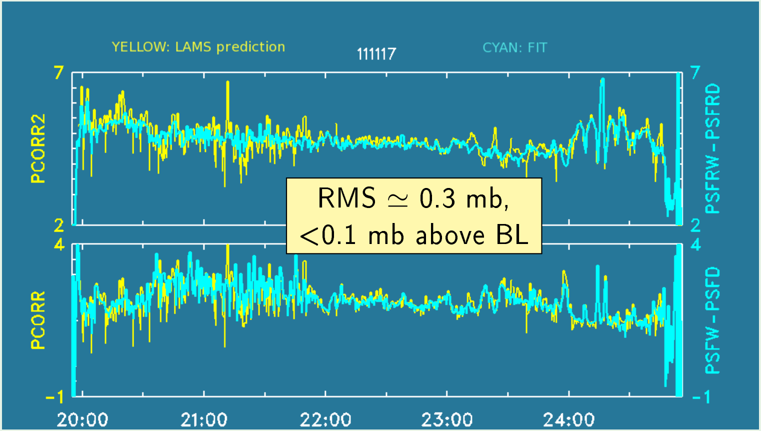
Procedure:

1. Determine b_2 from sideslip maneubers
2. Determine $b_1$from pitch maneuvers
3. With b_1 and b_2 fixed, find b_0 and b_2 using data from all times when LAMS provides a measurement of v.

Result:

- Better performance in maneuvers
- Slightly higher overall RMS

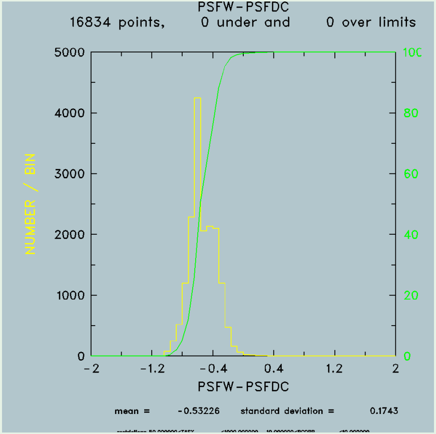
FIT (cyan) VS. LAMS PREDICTION (yellow)



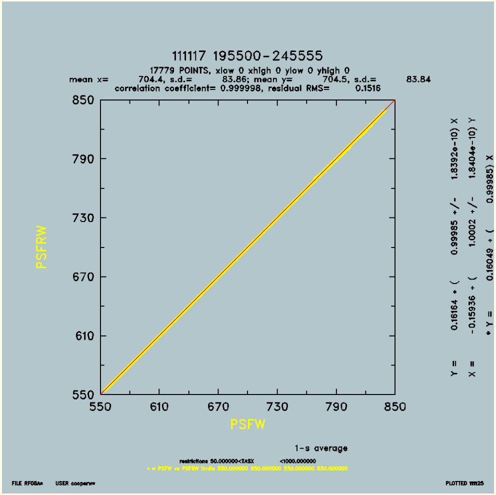
CHANGE FROM STANDARD?

PSFW: new calibration

- mean pressure is about 0.5 mb lower
- low scatter (<0.2 mb) $\Rightarrow$ functional dependence is similar



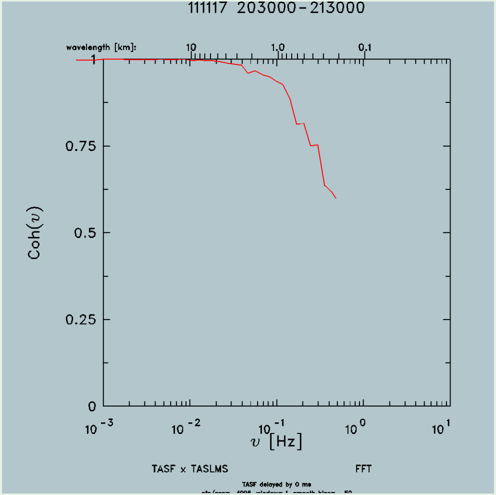
COMPARISON OF CORRECTED PSFD and PSFRD



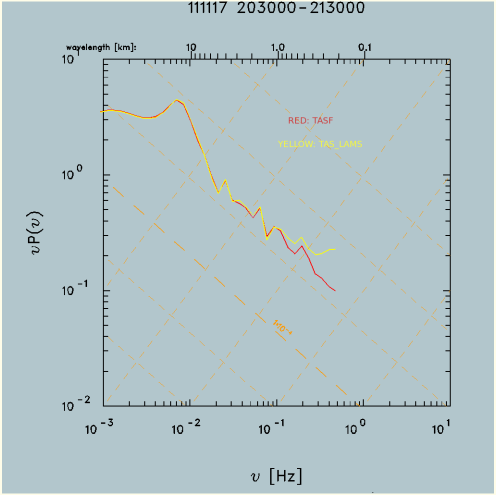
SOURCE OF NOISE?

Coherence, TASF vs TAS_LAMS

- boundary layer flight segment
- drops significantly by 5 Hz
- only 0.9 at 0.2 Hz



VARIANCE SPECTRA



REVERSE-HEADING FLIGHT SEGMENTS

Reverse-heading maneuvers flown on flight 5 of IDEAS-4:

Time Interval	UXW	GGTRK	THDG	WDC	WSC	UX
220000–230530	1.56±0.91	241	242	65	3.31	2.89
230700–231200	-1.08±0.55	59	59	224	1.43	-1.47
225100–225300	1.975±0.40	148	149	312	2.58	2.40
225500–225700	0.99±0.52	328	329	122	1.09	1.21

Test of Accuracy: Longitudinal Wind Should Reverse

- Set #1: ΔUXW≃0.5 m/s (vs. 1.4 m/s, std)
- Set #2: ΔUXW ≃ 3.0 m/s (vs 3.6 m/s, std)

CALIBRATING TEMPERATURE USING LAMS

Integrating the Hydrostatic Equation

- Assumption: absolute pressure is accurate as calibrated, LAMS
- GPS provides acurate measurement of geometric altitude
- Integrate the hydrostatic equation between two pressure levels:
    - Predicted altitude change depends on the “mean” temperature.
    - Comparison to a similar “mean” of the measurements checks the accuracy of the temperature measurement.

EQUATIONS USED

Three Sums Are Needed: S_1, S_2, S_3:

$$\delta p_i = -\frac{g\, p_i}{R_a\, T_{a,i}} \delta z_i \quad (\mathrm{too\, noisy,\, second-by-second})$$

$$S_1 = \sum_i \frac{R_{a,i}}{g_i} \ln\left(\frac{p_i}{p_{i-1}}\right)$$

$$S_2 = \sum_i (z_i - z_{i-1})$$

$$S_3 = \sum_i \frac{z_i - z_{i-1}}{T_{m,i}}$$

Then compare prediction (T_p) to observed (T_m)

$T_p = -S_1/S_2$ and $\overline{T}_m = S_2/S_3$, weighted appropriately

RESULTS FOR MEAN TEMPERATURES BETWEEN LAYERS

Flight Segment	T_p	$\overline{T}_m$	ΔT
RF05, 205800–211100	-10.98	-10.37	-0.5
RF07, 212510–213300	-6.36	-5.89	-0.47
RF07, 212510–212900	2.27	2.42	-0.15
RF07, 212900–213300	-12.85	-12.15	-0.70
RF08, 214500–215300	-0.9	-0.5	-0.4
RF08, 233700–234130	-6.5	-6.3	-0.4
RF08, 234500–235000	-9.4	-8.8	-0.6
RF08, 235600–240100	-9.5	-8.4	-1.1
mean offset[a], $T_p - \overline{T}_m$			-0.55

[a] excluding the first listed value for RF07 because the next two break this climb segment into two segments

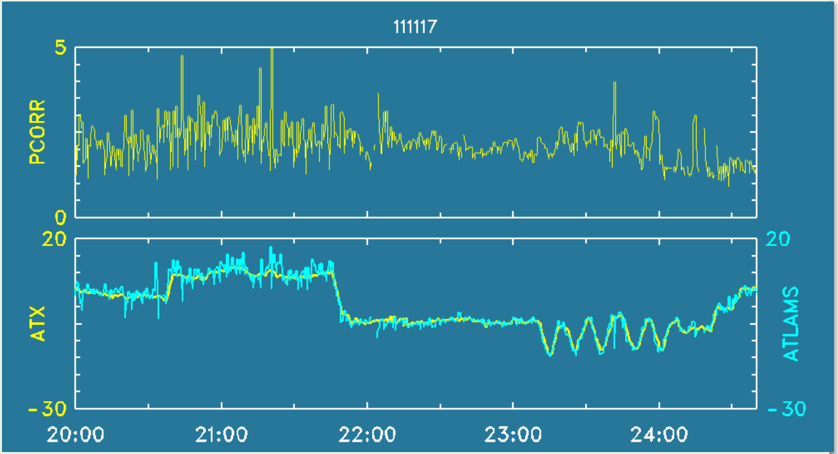
DETERMINING THE MACH NUMBER

$$M^2 = \left\{ \left(\frac{2c_v}{R_a} \right) \left[\left(\frac{p+q}{\mathrm{p}} \right)^{R_a/c_p} - 1 \right] \right\}$$

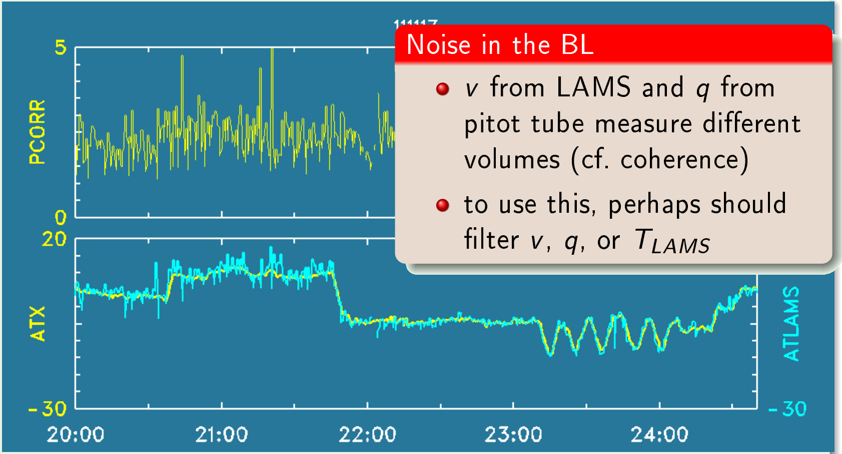
- LAMS provides a correction Δp to be added to p and subtracted from q (affecting only the denominator).
- Measured temperatue is not needed (except indirectly as it enters fitting to find Δp).
- Once calibrated, the above equation for M^2 can be used to find the temperature, independent of a temperature probe, using only pressure measurements and v determined by LAMS::

$$T_{LAMS} = v^2/(\gamma R_a M^2)$$

AN EXAMPLE OF T FROM LAMS



AN EXAMPLE OF T FROM LAMS



Noise in the BL

- v from LAMS and q from pitot tube measure different volumes (cf. coherence)
- to use this, perhaps should filter v, q, or T_{LAMS}

Key Results:

1. LAMS provides a direct calibration of airspeed.
    - TAS_LAMS is slightly higher than TASX
2. This calibrates dynamic pressure:
    - q should be increased by about 0.5 mb on average.
3. If total pressure is accurately measured, this calibrates pressure:
    - p should be decreased by about 0.5 mb on average.
4. Accurate pressure supports integration of the hydrostatic equation to calibrate temperature:
    - Results indicate that temperature should be decreased by about 0.5°C.
5. It is then possible to derive a new temperature measurement solely from p, q, and v_{LAMS}.