Influence of environmental parameters on calibration drift in superconducting RF cavities

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Background

- Precisely calibrating RF forward (Vf) and the reflected signals (Vr) are crucial for accurately assessing **cavity bandwidth and detuning**.
- However, the **finite directivity of waveguide directional couplers** affect the measurement of signals V_F^m and V_R^m.
- Also, **calibration drifts caused by humidity and temperature fluctuations** pose a challenge to the calibration of RF signals.
- **Long-term calibration drifts** should be analyzed, predicted, and compensated.

RF Signal Calibration

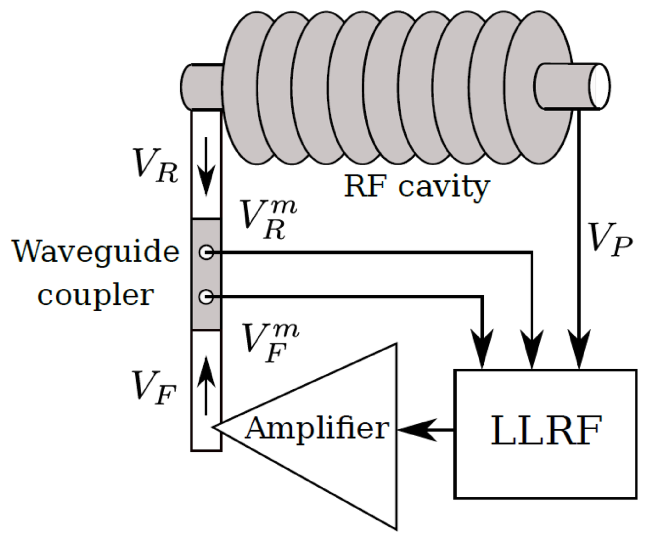
To correct the measured RF signals V_F^m and V_R^m due to finite directivity of waveguide coupler, a calibration matrix is applied.

$$V_F = aV_F^m + bV_R^m$$
$$V_R = cV_F^m + dV_R^m$$

The vitrual probe is defined by summing the calibrated RF signals V_F and V_R:

$$V_P^V = V_F + V_R = XV_F^m + YV_R^m$$

$$X = (a+c)\ for\ V_F^m$$
$$Y = (b+d)\ for\ V_R^m$$



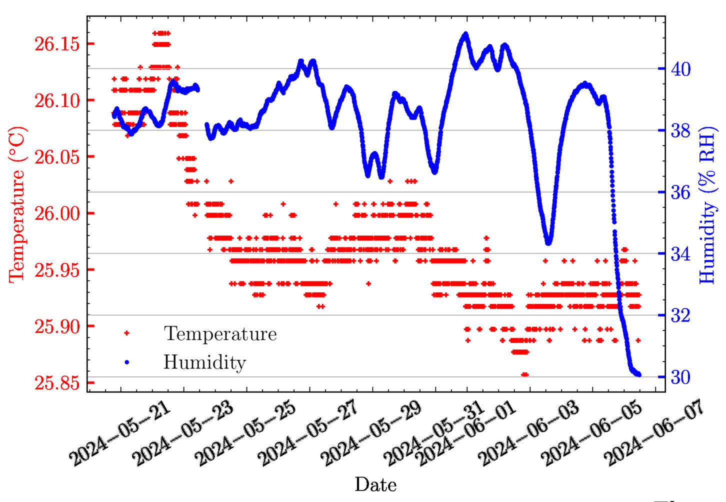
A. Bellandi, et al. Nucl. Instr. Meth. Phys. Res. Section A, 169172 (2024).

Calibration error is defined as the difference between the measured probe signal V_P^m and the vitual probe V_P^V:

$$E_A = \sum_{i=0}^{N=16k} \left|V_{P\,i}^m - V_{P\,i}^V\right| / N \qquad E_P = \sum_{i=0}^{N=16k} phase\left(V_{P\,i}^m - V_{P\,i}^V\right) / N$$

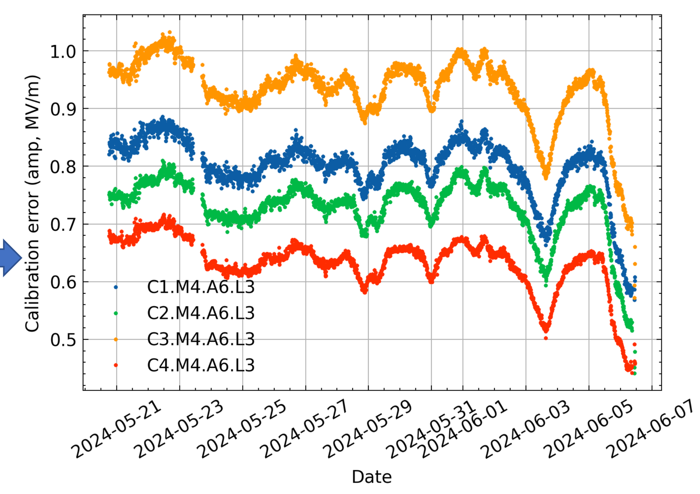
Calibration Drift

Humidity and temperature fluctuations



Temperature is more stable than humidity, which is not actively controlled.

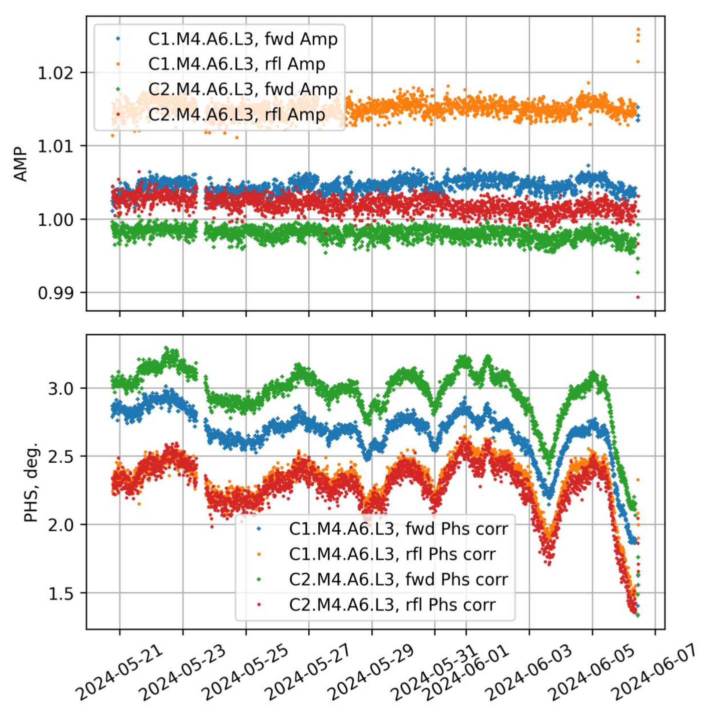
Long-term calibration drift (E_A)



The amplitude of the calibration errors E_A fluctuate with environmental factors.

Recalibrate RF Signals and Correlation Analysis

- **Calibration is achieved by performing a nonlinear least square optimization constrained by energy conservation laws** (*A. Bellandi, et al. Nucl. Instr. Meth. Phys. Res. Section A, 169172 (2024)*).
- **Amplitude and phase corrections are applied to RF signals V_F^m and V_R^m.**

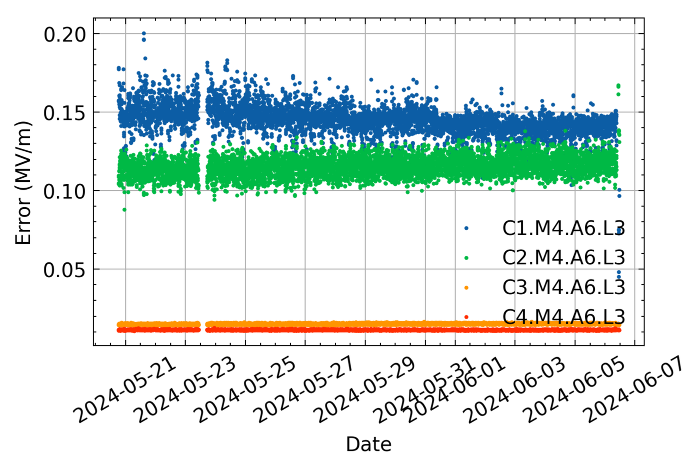


$|X|$ for V_F^m

$|Y|$ for V_R^m

$Phs(X)$ for V_F^m

$Phs(Y)$ for V_R^m

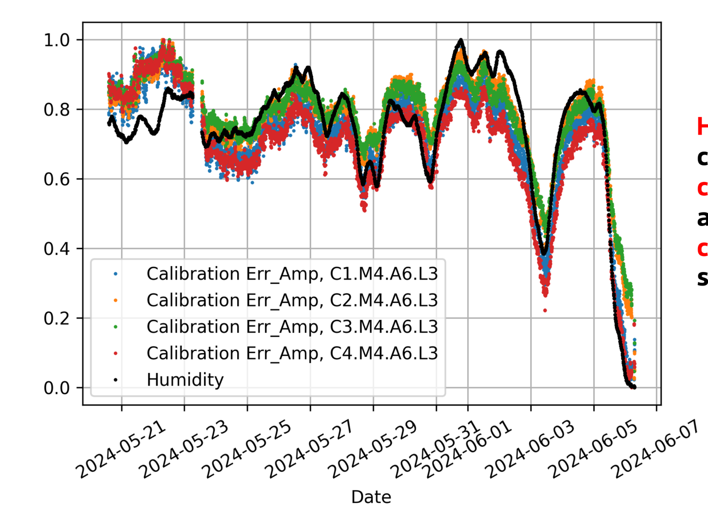


Error after recalibration

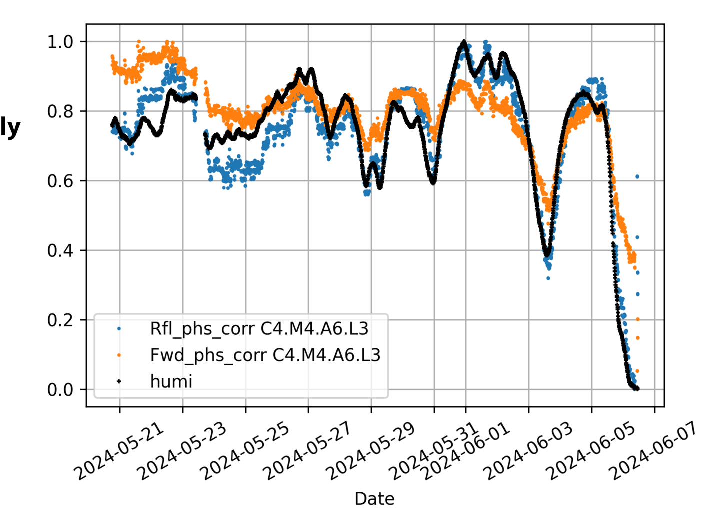
Calibration is performed for each signal.

- The amplitude of the applied calibration coefficients is stable.
- The phase of the calibration coefficients fluctuate with environmental factors.

- **Correlation analysis of humidity, calibration error, and recalibration coefficients**

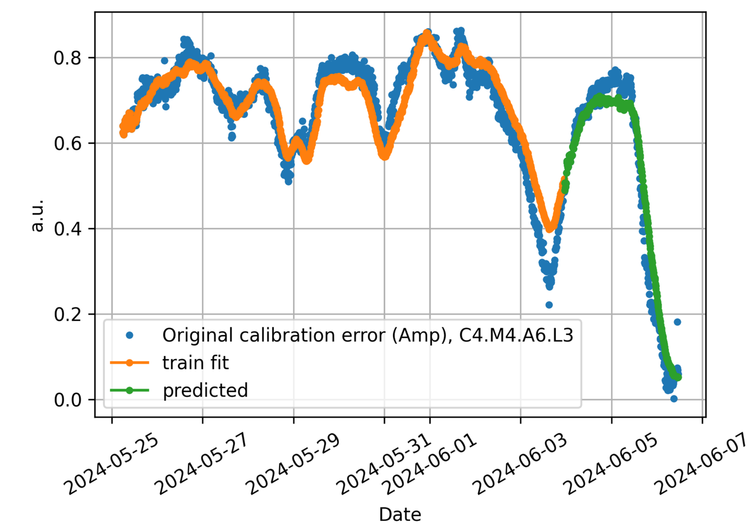


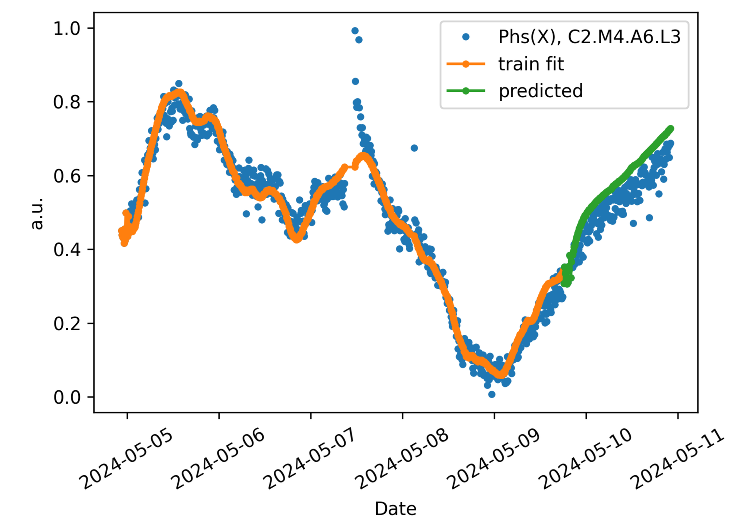
Humidity is strongly correlated to calibration errors and applied phase corrections to RF signals V_F^m and V_R^m

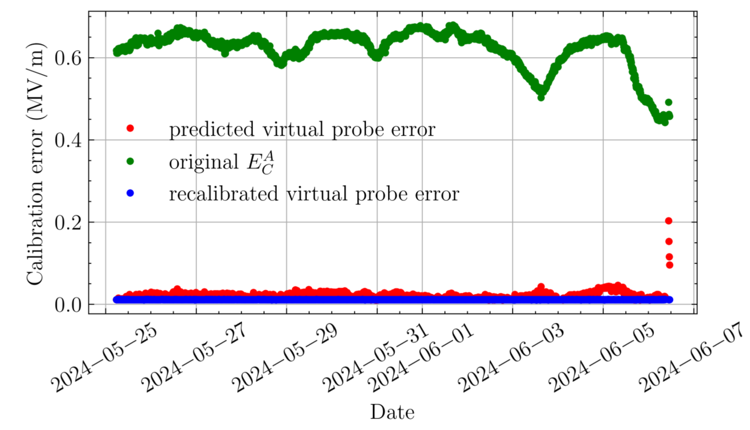


Predicting Calibration Error and Phase Correction Results

- **Predicting calibration errors, calibration coneffiecients, and phase corrections of RF signals with the Sysidentpy Package**
- **Splitting Data: 80% for Training, 20% for Validation**
  - Data collected every 10 mins for 1 week or 2 weeks



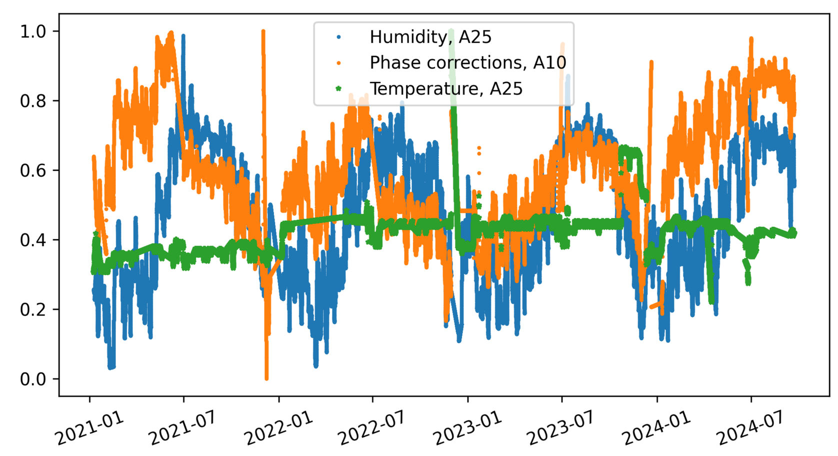




- **Build Polynomial NARMAX Models using FROLS (Forward Regression Orthogonal Least Squares)**
- **Predictions are based on both humidity and temperature**
- **The results also suggest that the validity of the fitting and prediction periods should be determined**

Calibration error based on the predicted calibration coefficients.

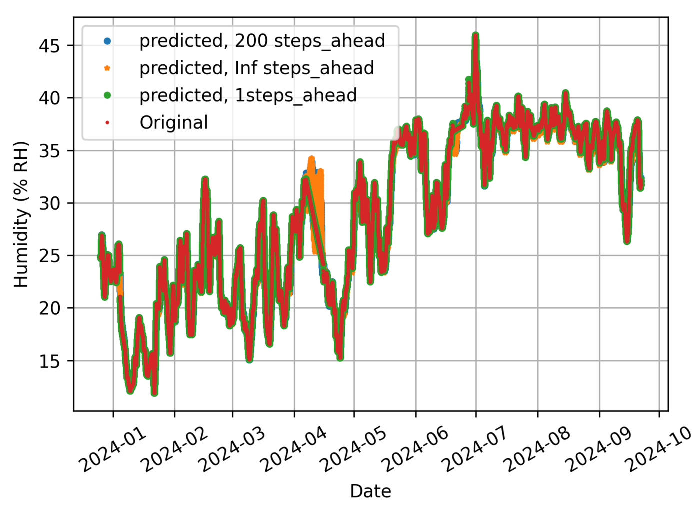
Historical Data Analysis and Preliminary Results



- Historical data were collected for all stations (one cavity each for M12, M34);
- Data from A7, A10, A11, A13, A19, and A25 were analyzed;
- Data preprocessing:
  - Outliers removing
  - Data Interpolation with equal time intervals
  - Data normalization

Example historical humidity, temperature, and dynamic phase corrections for the past three years and nine months

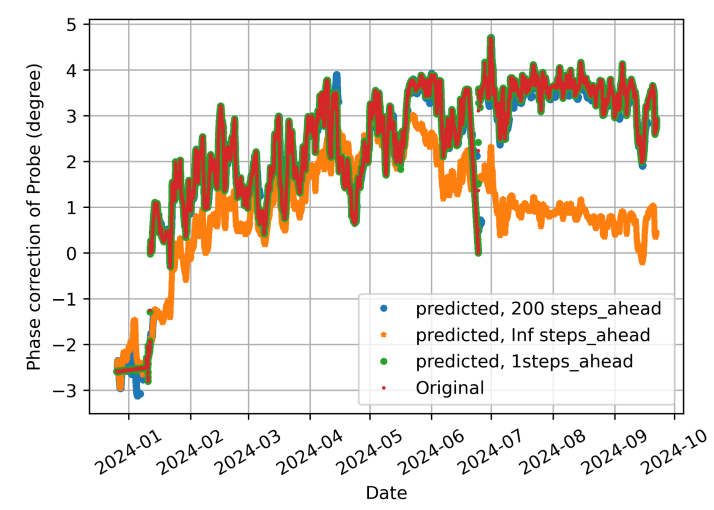
LINAC Environmental Model



Predicted humidity at station A25 based on humidity at stations A7, 11, 13 and A19.

Time interval of data: 0:16:40
200 steps ahead : 2 days, 7:33:20

Model for predicting phase corrections



Predict the dynamic phase correction for the probe signal at station A10 based on the humidity and temperature at stations A7, A11, A13, A19, and A25.

- **Predicted by the Sysidentpy Package**
  The order of the polynomial model is set to 2 and the number of regressors to 22 or 30.
- Environmental models can be used to predict local humidity/temperature for any given cavity
- Predictions of phase corrections to probe signals show that phase corrections to forward and reflected signals can also be predicted.

Summary and Future Work

- Long-term calibration drift analysis
- Correlation analysis of calibration errors and calibration coefficients with environmental factors
- Prediction of calibration error and phase correction based on environmental factors
- Historical Data Analysis: environmental model and model for predicting phase corrections

- Longer-term data analysis need to be validated
- Analysis of calibration error with the fitting based on Sysidentpy package
- Calibration thresholds: when to calibrate, especially in CW mode

Reference

F. Qiu et al. Nucl. Instr. Meth. Phys. Res. *Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1034*, 166769 (2022).
A. Bellandi, et al. Nucl. Instr. Meth. Phys. Res. *Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 169172 (2024).
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