EUROPEAN UNION
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Operational Programme Research, Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS

AoP long term evolution

The sweep algorithm

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FZU
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Area over peak - Data selection and cuts

Data taken from the monitoring files *mc_yyyy_mm_dd_HHhMM.root*

Follow the long term studies for $\langle AoP \rangle$ described in GAP 2012-154 as close as possible

7 more years of data!!!

Data selection and cuts

- Period from 1 January 2004 to 31 December 2018
- Data binned in one week intervals

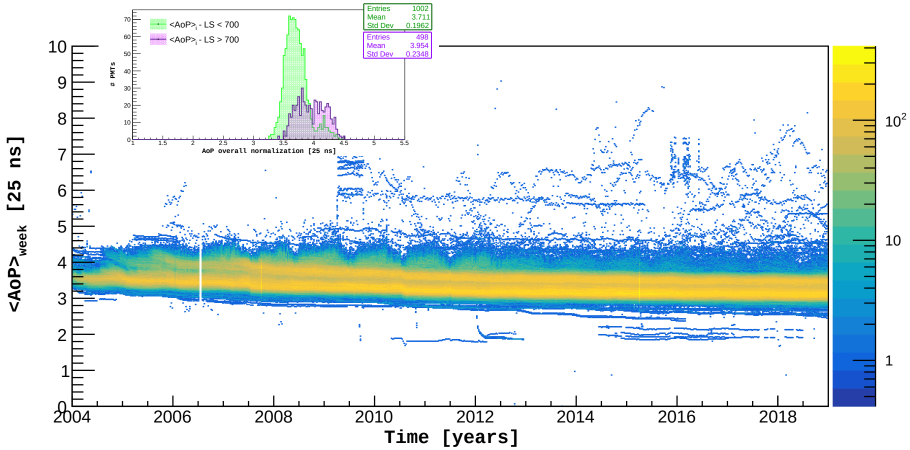
- Select only PMTS where - $T1 > 0$
- $Area > 0$
- $Peak > 0$

- Station has 3 working PMTs (unmasked) - $TubeMask == 7 || TubeMask == 15$
  - Periods with masked PMTs are not used in the analysis

- Remove periods where the PMT is raining
  - $Var\,(Dynode/Anode) < 4.5$
  - Sweep algorithm
    - Discard PMTs where there are more than 4 cases where $1 - \langle AoP \rangle_{i+1} / \langle AoP \rangle_i > 1\%$
- Consider only PMTs which have more than 3 years of data
- PMTs pass a set of fitting cuts

Area over peak - An overall view

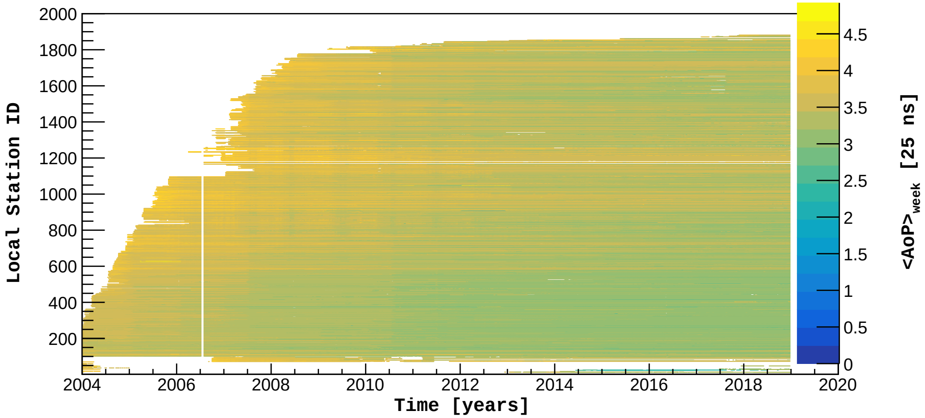
No cuts, all the PMTs



Evidence of 2 populations of the initial value of $\langle AoP \rangle$

Area over peak - An overall view

No cuts, all the PMTs

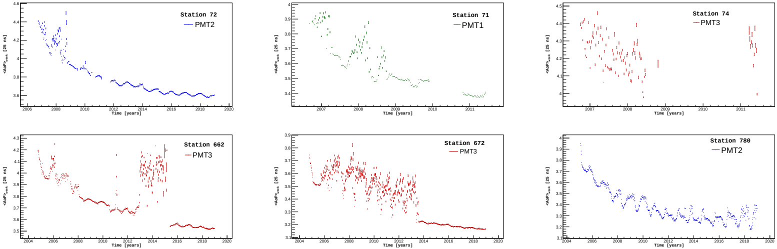


Area over peak - Sweep algorithm

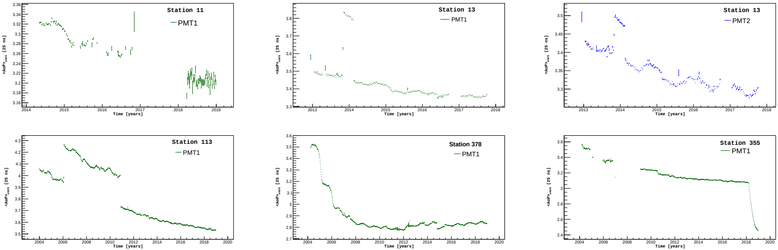
As suggested in GAP 2012-154:

- Remove PMTs where the variation in adjacent $\langle AoP \rangle$ bins exceeds 1% more than 4 times

Excluded by the sweep algorithm

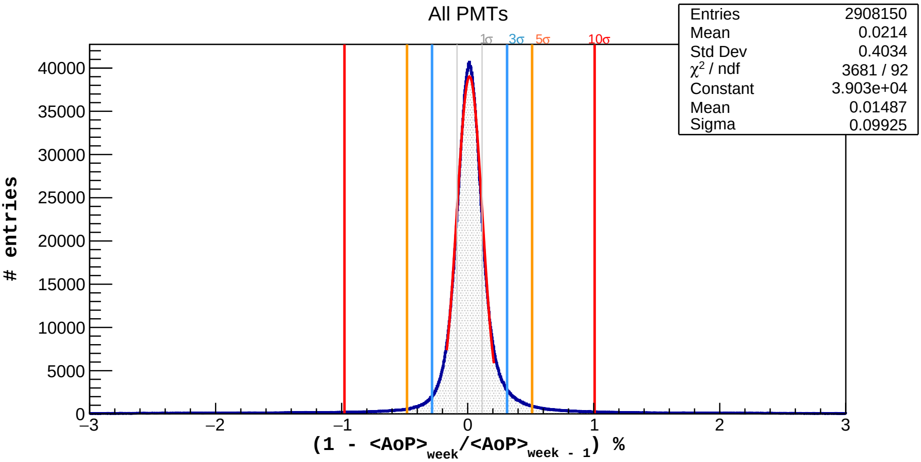


Passed the sweep algorithm



$\langle AoP \rangle$ jumps

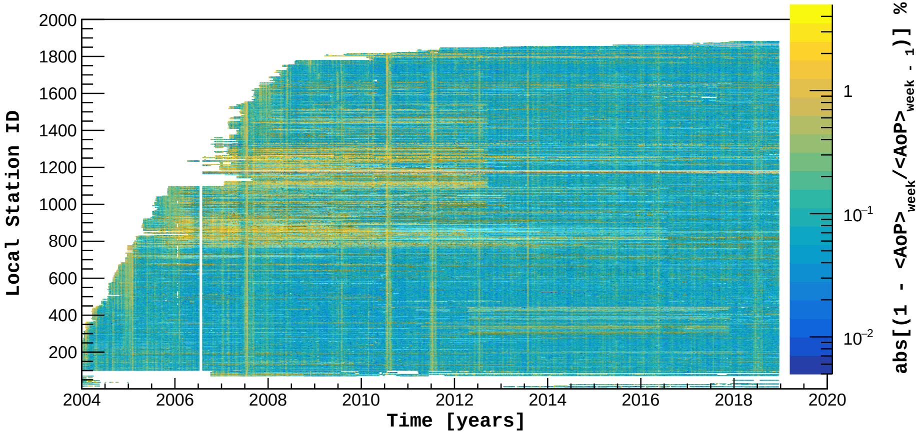
All $\langle AoP \rangle$ variation in consecutive time bins - No cuts, all the PMTs



The cut in the $1 - \langle AoP \rangle_{i+1} \, / \, \langle AoP \rangle_i > 1\%$ is a cut at 10σ deviation of the overall distribution

$\langle AoP \rangle$ jumps - Time analysis

All $\langle AoP \rangle$ variation in consecutive time bins - No cuts, all the PMTs

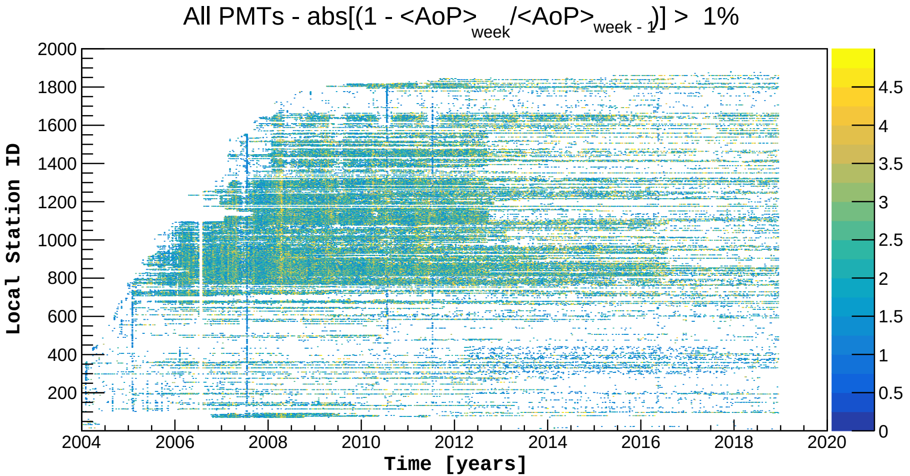


Stations with IDs between 700 to 1600 present a high number of jumps

The freezing events are also evident

$\langle AoP \rangle$ jumps - Time analysis

Selecting the cases where the $\langle AoP \rangle$ jumps are $> 1\%$ - All the PMTs

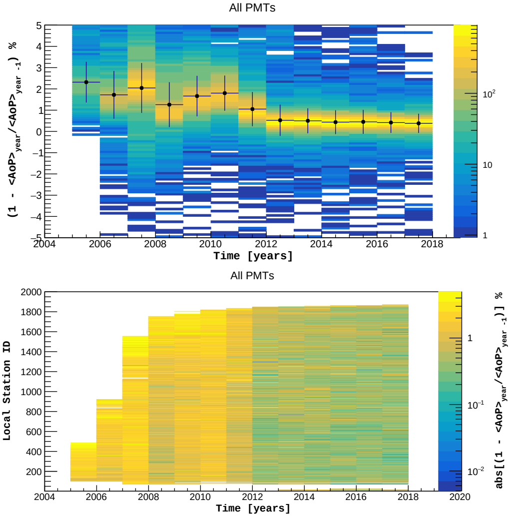


Stations with IDs between 700 to 1600 present a high number of jumps

The freezing events are also evident

$\langle AoP \rangle$ jumps - Time analysis

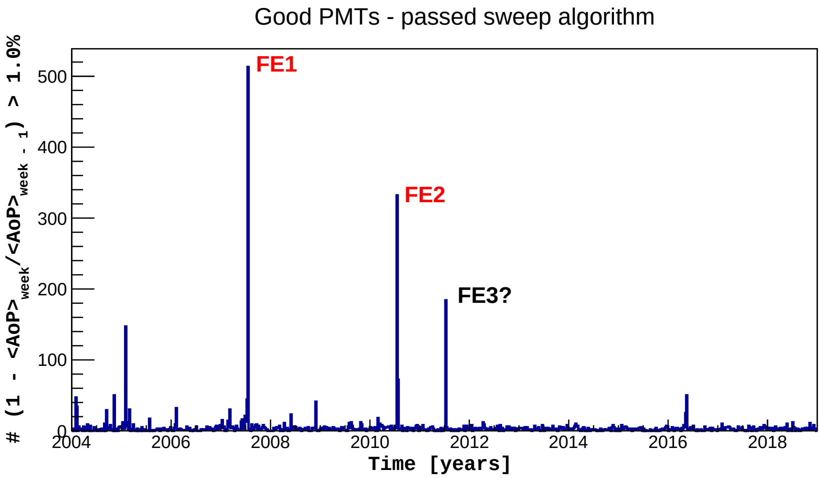
In 2012 a campaign to fix the raining/bad PMTs started in the field



Array seems to stabilize after 2012 (fixing the raining PMTs?)

$\langle AoP \rangle$ jumps - Time analysis

$\langle AoP \rangle$ **variation in consecutive time bins - PMTs which pass the sweep algorithm**



Area over peak - 2007 and 2010 "freezing events"

Freezing events of 2007 and 2010 are a very known effect

GAP 2012-154

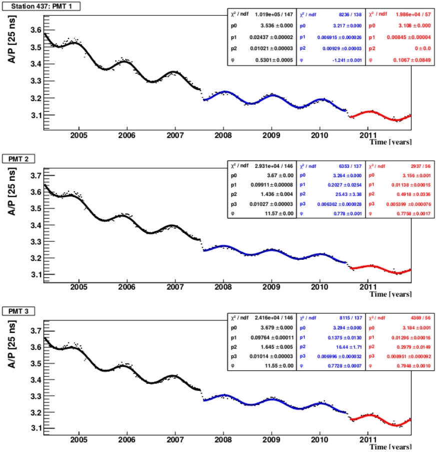


Figure 4: Evolution of A/P for station 437, with three different fits, before, between and after mid July of winters 2007 and 2010.

- Unusual temperatures below of $-15°C$ in Malargüe
- $10\,\mathrm{cm}$ thick layer of ice observed in the stations
  - Drop of $\langle AoP \rangle \sim 1-3\%$
- Proposed approach:
  - Fit the data into 3 periods:
    - Before FE1
    - Between FE1 and FE2
    - After FE2
  - Recommendable to have a minimum of 3 years of data for the fit

Area over peak - Fitting

Fit function:

$$\langle AoP \rangle (t) = \mathbf{p_0} \left[1 - \mathbf{p_1} \left(1 - e^{-\frac{t-t_0}{\mathbf{p_2}}} \right) \right] \left[1 + \mathbf{p_3} \sin \left(2\pi \left(\frac{t-t_0}{T} - \phi \right) \right) \right]$$

Fit parameter values, as proposed in R. Sato, for the Pierre Auger Collaboration, ICRC 2011:

- $1.0 \leq p_0 \leq 5.5$ - $\langle AoP \rangle$ normalization
- $0.0 \leq p_1 \leq 1.0$ - Fractional loss
- $0.0 \leq p_2 \leq 500$ - Characteristic time in years
- $0.0 \leq p_3 \leq 1.0$ - Seasonal amplitude
- ϕ - Phase

Further constraints:

- Fit converges
- $\chi^2/NDF < 2000.0$
- $NDF > 40$
- Only PMTs passing all the fit periods are accounted

All the 5 fit parameters are free

Area over peak - Fitting periods

PMTs operating before 2007 (the ones used in the previous analysis)

- Period1 - $\langle AoP \rangle_0 \leq t[\text{years}] \leq FE1$
- Period2 - $FE1 \leq t$ [years] $\leq FE2$
- Period3 - $FE2 \leq t$ [years] ≤ 2012 (only for comparison with GAP 2012-154)
- Period4 - $FE2 \leq t$ [years] $\leq \langle AoP \rangle_f$

PMTs operating after 2007 (the new ones)

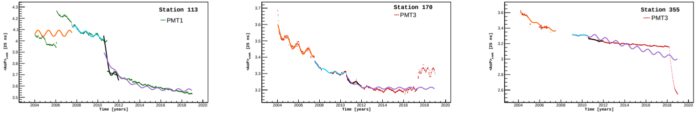
- $\langle AoP \rangle_0 < FE1$
  - Period2 extended - $\langle AoP \rangle_0 \leq t \; [years] \leq FE2$
  - Period4 - $FE2 \leq t$ [years] $\leq \langle AoP \rangle_f$
- $FE1 < \langle AoP \rangle_0 < FE2$
  - Period2 - $\langle AoP \rangle_0 \leq t \; [years] \leq FE2$
  - Period4 - $FE2 \leq t$ [years] $\leq \langle AoP \rangle_f$
- $\langle AoP \rangle_0 > FE2$
  - Period4 - $\langle AoP \rangle_0 \leq t$ [years] $\leq \langle AoP \rangle_f$

Area over peak - Fitting the AoP time evolution

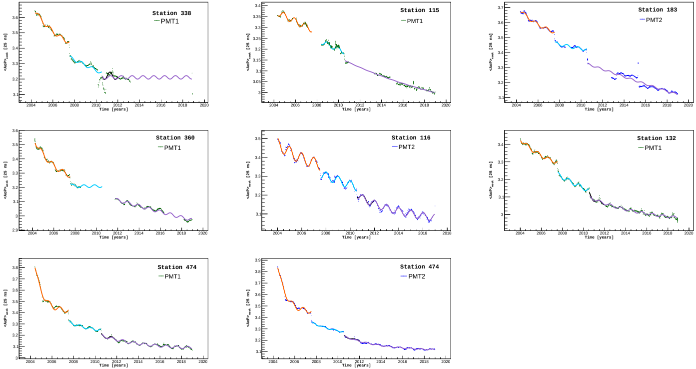
As suggested in GAP 2012-154:

- Remove PMTs which do not pass all the fitting criteria in all periods

Did not pass the fitting criteria



Passed the fitting criteria



Area over peak - Selection cuts

	Number of PMTs	Fraction
All PMTs	5690	
Have > 3 years of data	5097	89.6%
Passed the sweep algorithm	3505	61.6%
Passed the fit	2724	47.9%

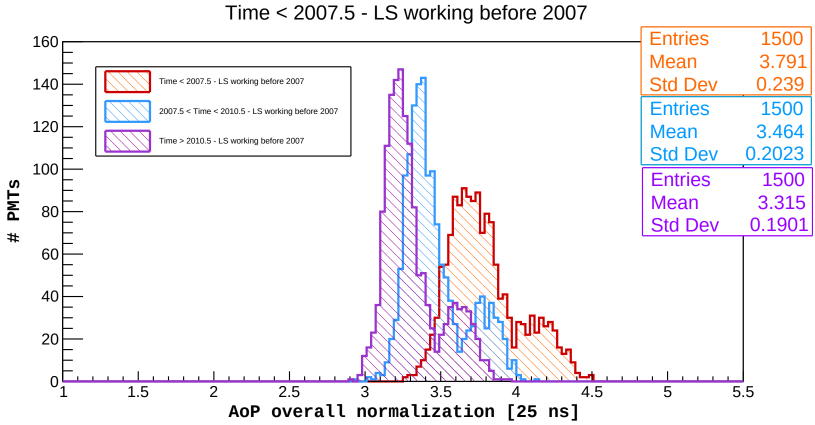
PMTs working before 2007	Number of PMTs	Fraction
Passed the sweep algorithm	2106 / 3505	60.1%
Passed the fit - Period1 && Period2 && Period3	1384 / 2724	50.8%
Passed the fit - Period1 && Period2 && Period4	1500 / 2724	55.1%

PMTs working after 2007	Number of PMTs	Fraction
Passed the sweep algorithm	1399 / 3505	39.9%
Passed the fit - Period2 extended && Period4	456 / 2724	16.7%
Passed the fit - Period2 && Period4	621 / 2724	22.8%
Passed the fit - Period4	147 / 2724	5.4%

Area over peak - Results

$$\langle AoP \rangle (t) = \mathbf{p_0} \left[1 - p_1 \left(1 - e^{-\frac{t-t_0}{p_2}}\right)\right] \left[1 + p_3 \sin\left(2\pi \left(\frac{t-t_0}{T} - \phi\right)\right)\right]$$

- $1.0 \leq p_0 \leq 5.5$ - $\langle AoP \rangle$ normalization

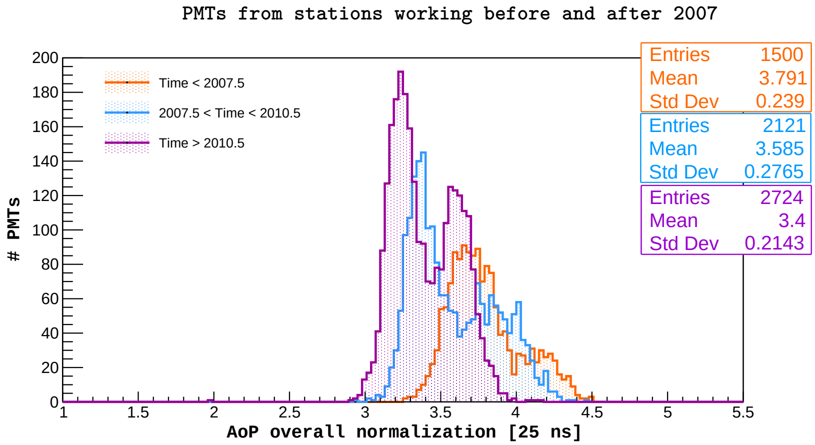


Gradual decrease of the $\langle AoP \rangle$ at each period

Area over peak - Results

$$\langle AoP\rangle(t) = \mathbf{p_0}\left[1 - p_1\left(1 - e^{-\frac{t-t_0}{p_2}}\right)\right]\left[1 + p_3\sin\left(2\pi\left(\frac{t-t_0}{T} - \phi\right)\right)\right]$$

- $1.0 \leq p_0 \leq 5.5$ - $\langle AoP\rangle$ normalization



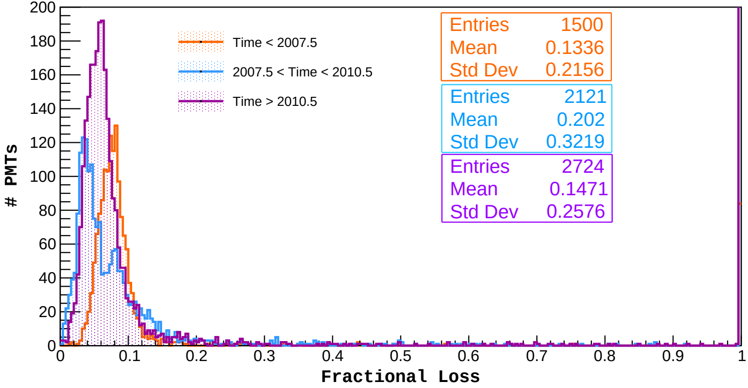
Gradual decrease of the $\langle AoP\rangle$ at each period

Area over peak - Results

$$\langle AoP\rangle(t) = p_0\left[1 - \mathbf{p_1}\left(1 - e^{-\frac{t-t_0}{p_2}}\right)\right]\left[1 + p_3\sin\left(2\pi\left(\frac{t-t_0}{T} - \phi\right)\right)\right]$$

- $0.0 \leq p_1 \leq 1.0$ - Fractional loss

PMTs from stations working before and after 2007

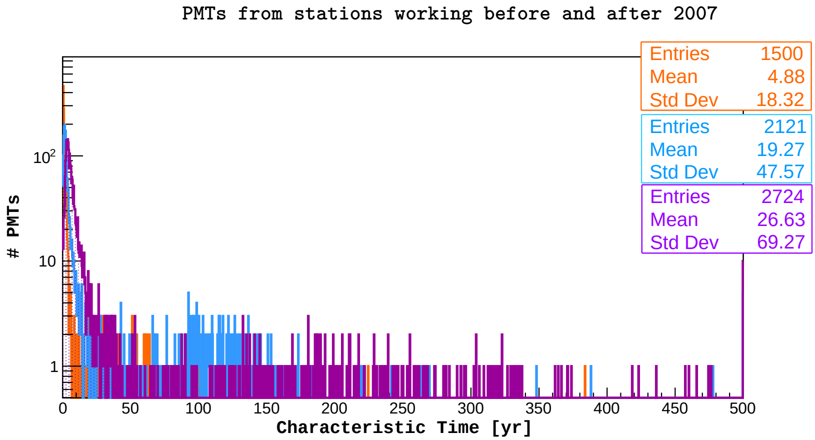


Large fraction of fits converged at the limit!!

Area over peak - Results

$$\langle AoP \rangle (t) = p_0 \left[1 - p_1 \left(1 - e^{-\frac{t - t_0}{\mathbf{p_2}}} \right) \right] \left[1 + p_3 \sin \left(2\pi \left(\frac{t - t_0}{T} - \phi \right) \right) \right]$$

- $0.0 \leq p_2 \leq 500$ - Characteristic time in years



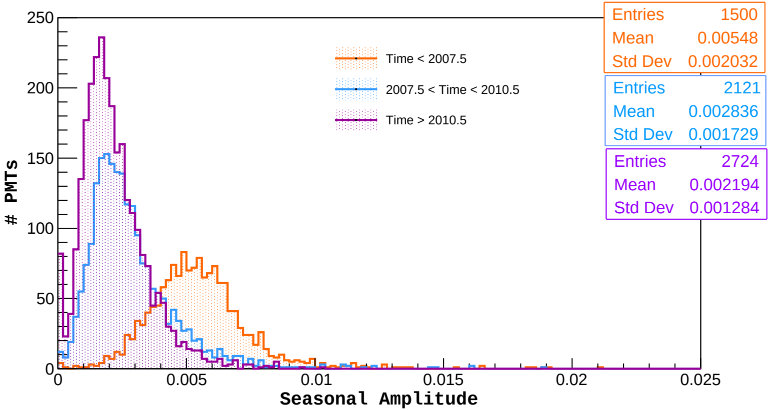
Characteristic time increases with the station age

Area over peak - Results

$$\langle AoP \rangle (t) = p_0 \left[1 - p_1 \left(1 - e^{-\frac{t-t_0}{p_2}}\right)\right] \left[1 + \mathbf{p_3} \sin\left(2\pi \left(\frac{t-t_0}{T} - \phi\right)\right)\right]$$

- $0.0 \leq p_3 \leq 1.0$ - Seasonal amplitude

PMTs from stations working before and after 2007



Seasonal amplitude stabilized after Period2

Seasonal effects reduced in many stations after 2012

Area over peak - Estimated loss of AoP

In GAP 2012-154 it is estimated that the estimated $\langle AoP \rangle_{2020}$ will be larger than 85% in most cases

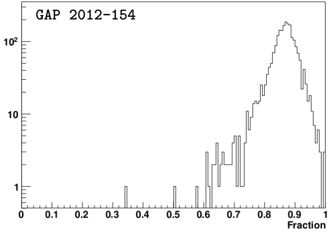
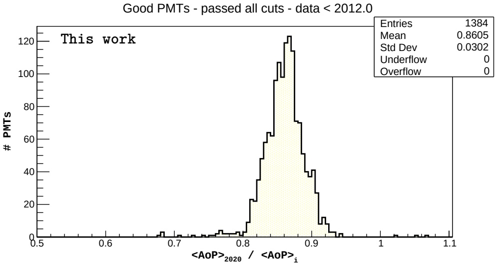


Figure 8: Estimated relative values (Fraction) of A/P for year 2020 with respect to its initial value.

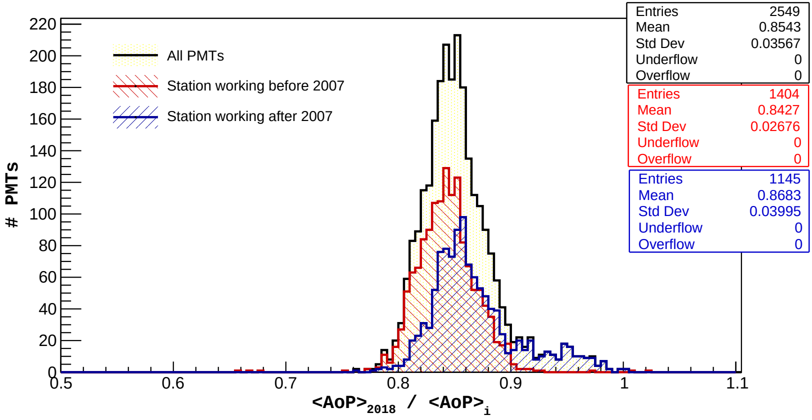
In this work:

- 40% of the stations lost more than 15% of its initial value
- Number of PMTs is compatible of what is reported in GAP 2012-154
- All the fit parameters are free
  - 80 PMTs have $p_1 \sim 1.0$ in Period1



Area over peak - Estimated loss of AoP

All PMTs which pass all the cuts and have data points above 1 January 2018

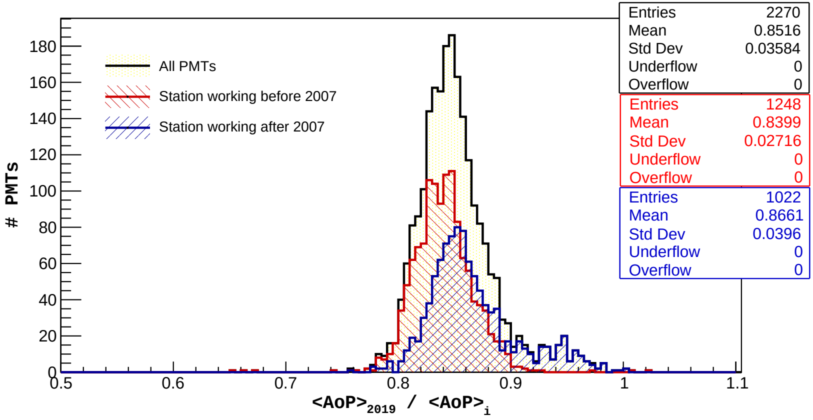


59% of the PMTs suffered a loss larger than 15%

72% (43%) of the PMTs working before (after) 2007 suffered a loss larger than 15%

Area over peak - Estimated loss of AoP

All PMTs which pass all the cuts and have data points above 2018.95

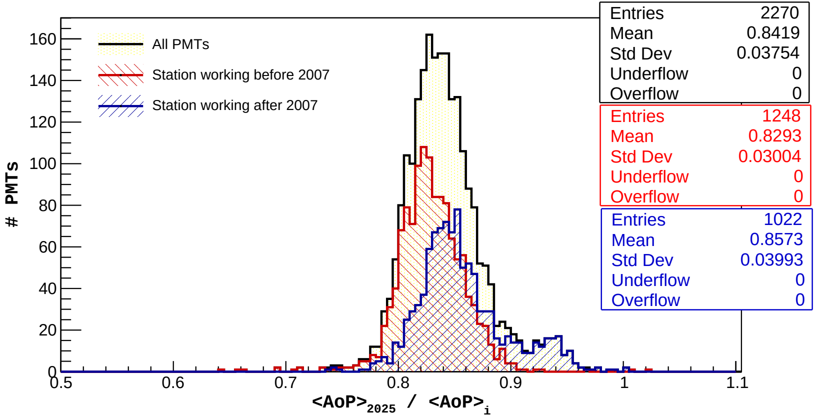


62% of the PMTs suffer a loss larger than 15%

75% (47%) of the PMTs working before (after) 2007 suffer a loss larger than 15%

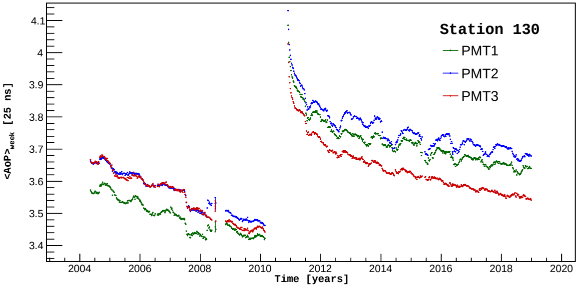
Area over peak - Estimated loss of AoP

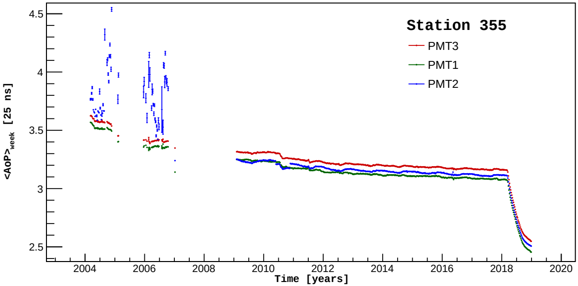
All PMTs which pass all the cuts and have data points above 15 December 2018



71% of the PMTs estimated to suffer a loss larger than 15%

83% (57%) of the PMTs working before (after) 2007 suffer a loss larger than 15%


Station 130
PMT1
PMT2
PMT3
<AoP>week [25 ns]
Time [years]


Station 355
PMT3
PMT1
PMT2
<AoP>week [25 ns]
Time [years]

Conclusions

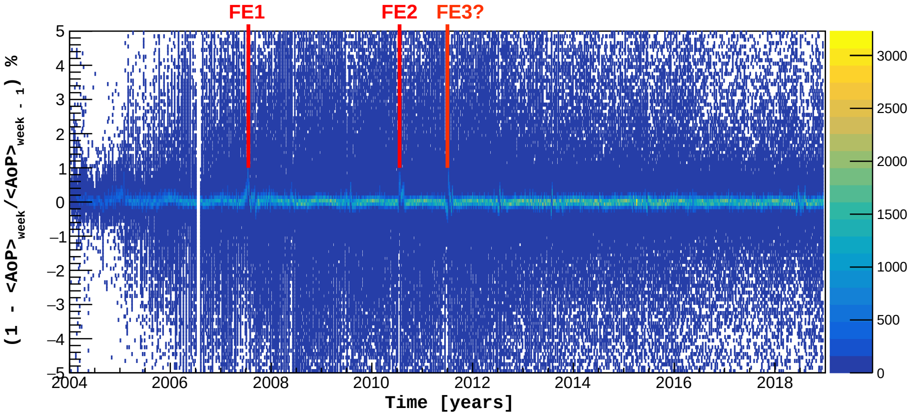
- Study of the evolution of the $\langle AoP \rangle$ since 1 January 2004 to 31 December 2018
  - Analysis based on the “official“ procedure as described in GAP 2012-154 and previous works
    - All fit parameters are set free
- Number of PMTs which pass the sweep algorithm and the long term fits seems to agree with previous works

- Loss of the $\langle AoP \rangle$ over time is observed
  - Loss is more important in the first years after deployment
- Array as a whole shows a more stable behavior after 2012
  - Continuous campaign to fix the raining PMTs
  - Maybe other effects play a role
- Larger fraction of loss of the initial $\langle AoP \rangle$ observed with this analysis
  - Average loss of the selected PMTs working after 2018.5 is 85%
  - 62% of the selected PMTs working after 2018.5 suffered a loss larger than 15%
    - 75% / (47%) of then were working before / (after) 2007
  - Estimated average loss of the selected PMTs working after 2018.5 in January 2025 is 84%
  - 71% of the selected PMTs working after 2018.5 estimated to suffer a loss larger than 15%
    - 83% / (57%) for PMTs working before / (after) 2007

Backup

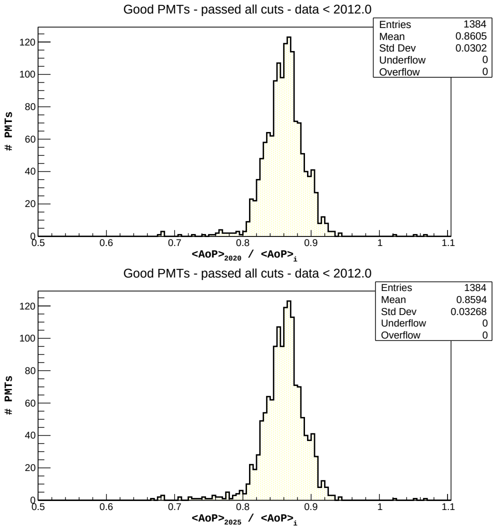
$\langle AoP \rangle$ jumps - Time analysis

All $\langle AoP \rangle$ variation in consecutive time bins - No cuts, all the PMTs



Area over peak - Estimated loss of AoP

In GAP 2012-154 it is estimated that the estimated $\langle AoP \rangle_{2020}$ will be larger than 85% in most cases

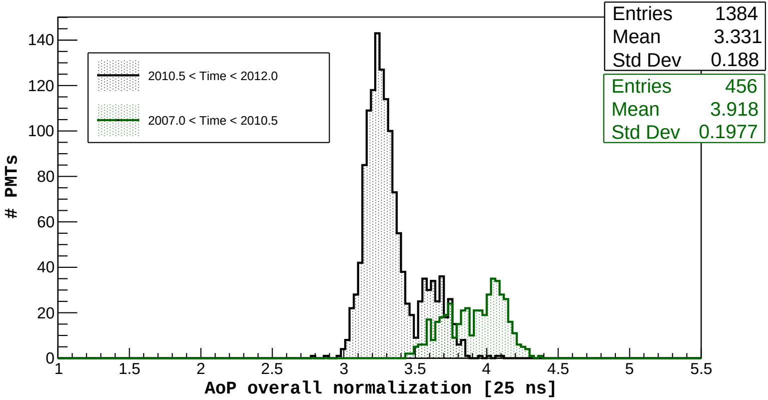


40% **of the PMTs suffer a loss larger than** 15%

Area over peak - Results

$$\langle AoP \rangle (t) = \mathbf{p_0} \left[1 - p_1 \left(1 - e^{-\frac{t-t_0}{p_2}}\right)\right] \left[1 + p_3 \sin\left(2\pi \left(\frac{t-t_0}{T} - \phi\right)\right)\right]$$

- $1.0 \leq p_0 \leq 5.5$ - $\langle AoP \rangle$ normalization



Gradual decrease of the $\langle AoP \rangle$ at each period, as expected

GAP 2012-154 AoP fit results

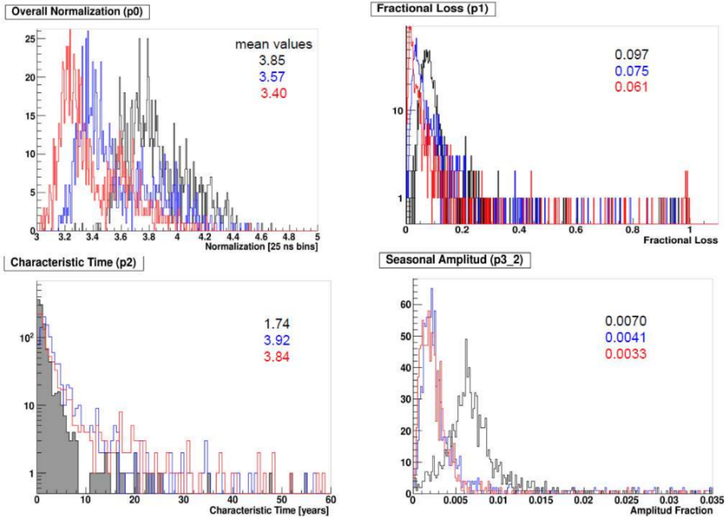
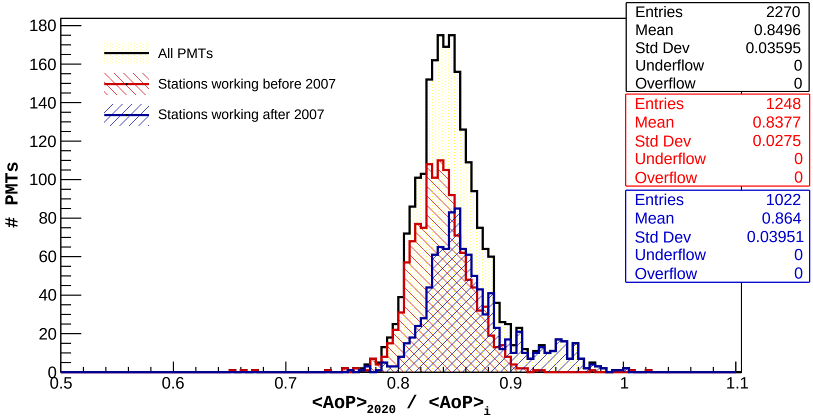


Figure 5: Parameters of the fit function for the three different periods, before and after freezing events of 2007 and 2010. Mean values of the distributions are displayed. Red: before 2007. Blue: Between 2007 and 2010. Black after 2010.

Area over peak - Estimated loss of AoP

All PMTs which pass all the cuts and have data points above 2018.95



65% of the PMTs estimated to suffer a loss larger than 15%

77% (50%) of the PMTs working before (after) 2007 suffer a loss larger than 15%