



## Stability of the SABR model

October 2016

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This article investigates the stability of the SABR parameters across a range of historical data. It describes some of the various factors that can affect the stability in both the Black and Normal calibration spaces.

# Introduction

Since its inception the SABR model has become the dominant market model for interest-rate derivatives. It owes its popularity to two main factors: Firstly, it models both the underlying forward rate and its volatility. This is an essential element in order for any model to reproduce the volatility smile. The second element is the derivation by Hagan *et al* of an approximate closed-form formula for the implied volatility in terms of the four SABR parameters. This is a key ingredient for quick calibration of the model to the market.

The closed form SABR formulas<sup>1</sup>, however, come with a number of disadvantages. A well-known weakness is the fact that the probability density function of the forward rate becomes negative for very low strikes. This is an artefact of the various asymptotic expansions that lead to the closed-form formula. This weakness becomes particularly important in the current negative-rate environment where derivatives are traded at negative or low strikes. The literature in the area of “fixing” the SABR model is quite rich, ranging from “quick and dirty”-type solutions, where a reasonably-behaving tail is attached to the body of the SABR PDF, to more elaborate variations of the SABR model.

For risk-management purposes a common question concerning the SABR model is about the stability of its parameters: An undesirable feature would be to have jumps in the SABR parameters across expiries or across valuation dates which would trigger other risk-management actions.

In this document, we present some visualizations concerning the evolution of the parameters. We also compare two versions of the SABR model encountered in practice, one that fixes the parameter beta to a positive value (typically to  $\beta=1/2$ ) and a second one that fixes beta to the value of zero.

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<sup>1</sup> See, for example, Hagan *et al* “Managing Smile Risk” Wilmott Magazine (7/2002), or, Berestycki *et al*. “Computing the implied volatility in stochastic volatility models” Comm. Pure Appl. Math., 57 1352, 2004

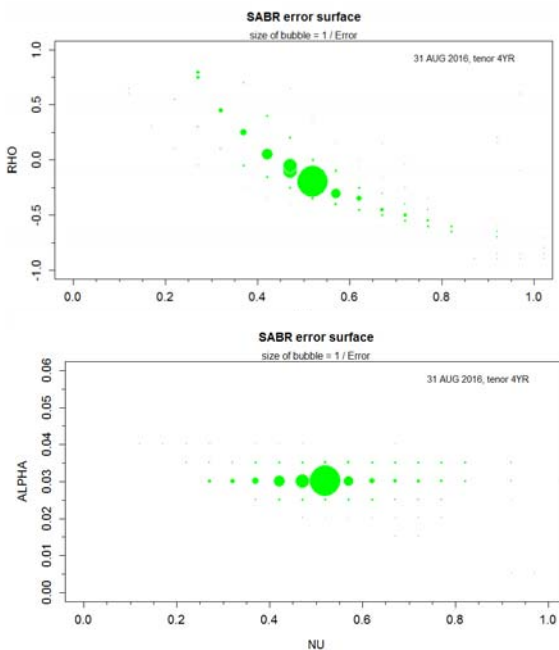
# Factors affecting stability

The SABR model carries four parameters (alpha, beta, rho, nu). According to common market practice the parameter beta is fixed to a certain value while the optimisation is run on the remaining three. The calibration error in the SABR model can be measured by, e.g. the sum of square errors between the market vols and the model vols.

The stability of the SABR model is affected by a series of factors some of which are:

## The number of local minima in the error surface

The SABR error surface that is generated in the space of (alpha, rho, nu) is described by a large number of local minima. In the two figures below we illustrate the location and depth of various local minima.



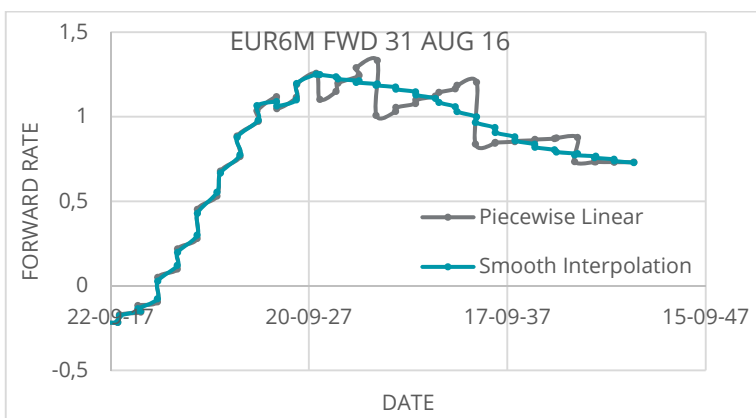
The size of the bubbles in these figures is inversely-proportional to the depth of the error surface, i.e. a large bubble would imply a small error. In these figures we see that global minimum of the SABR error surface is surrounded by a significant number of local minima (these figures are generated from the calibration of the EUR6M tenor as of 31 August 2016 on the 4YR expiry). As a result of this, a non-stochastic optimization algorithm may be trapped and not converge to the global optimum solution. Stochastic optimisation algorithms such as simulated annealing or genetic algorithms offer the advantage that at every new iteration step in the procedure they propose a move to a seemingly unfavourable location. This, however, offers the advantage that they can escape from local minima. Non-stochastic algorithms such as gradient descent or Levenberg-Marquardt do not offer this feature, although one way to incorporate stochasticity into the search would be to restart the optimiser from different initial conditions.

Because of the large number of local minima in the error surface, the convergence of the algorithm to different solutions may impact the smoothness of the SABR parameters.

### Discontinuities in the forward rate curve

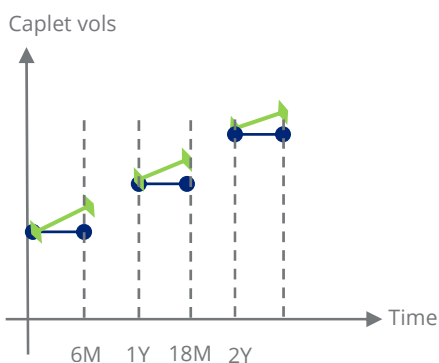
One of the parameters in the SABR formula is the forward rate. The term structure of the forward rate is usually bootstrapped from other market instruments. There is a certain number of choices that can be made in this procedure, for example, linear-interpolations versus spline-interpolations or interpolations in the spot-rate versus interpolations on the discount-curve, etc. Although all of these options are valid (as long as the price of the market instruments is reproduced correctly) they can lead to different behaviours of the forward curve and therefore different behaviours of the SABR parameters. The impact of this choice of the forward rate on the MTM can be quantified as a fraction of the Delta sensitivity.

An example of a forward curve built on two different interpolation assumptions is shown below.



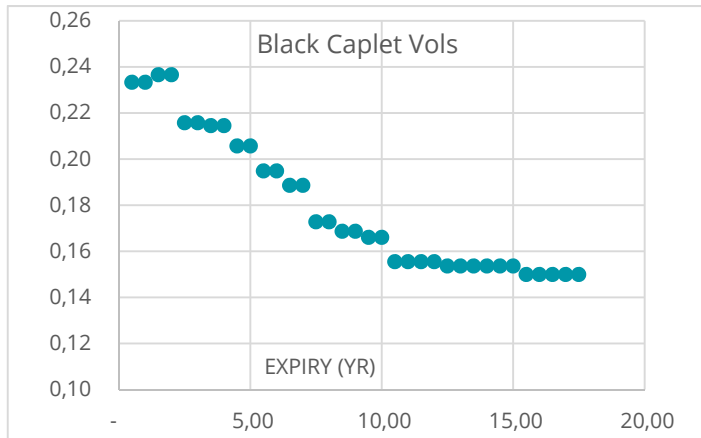
### Caplet stripping

The SABR formula expresses the implied caplet volatility in terms of the SABR parameters. However, caplet vols are not immediately quoted in the market. Rather, it is cap vols that are quoted, mainly for efficiency reasons. As a result of this unavailability, caplet vols need to be generated from the cap vols. There is no unique way to do this and there are various possible options that are all valid as long as the input market instruments are repriced correctly. The simplest possible approach would be to assume that caplet vols that fall between two quoted cap expiries are equal. This would be the “flat” interpolation. More elaborate assumptions would be to assume some term-structure of the caplet vols in-between expiries. The figure below illustrates schematically this difference.



The blue markers correspond to the “flat” caplet vol assumption while the green markers to an interpolation scheme.

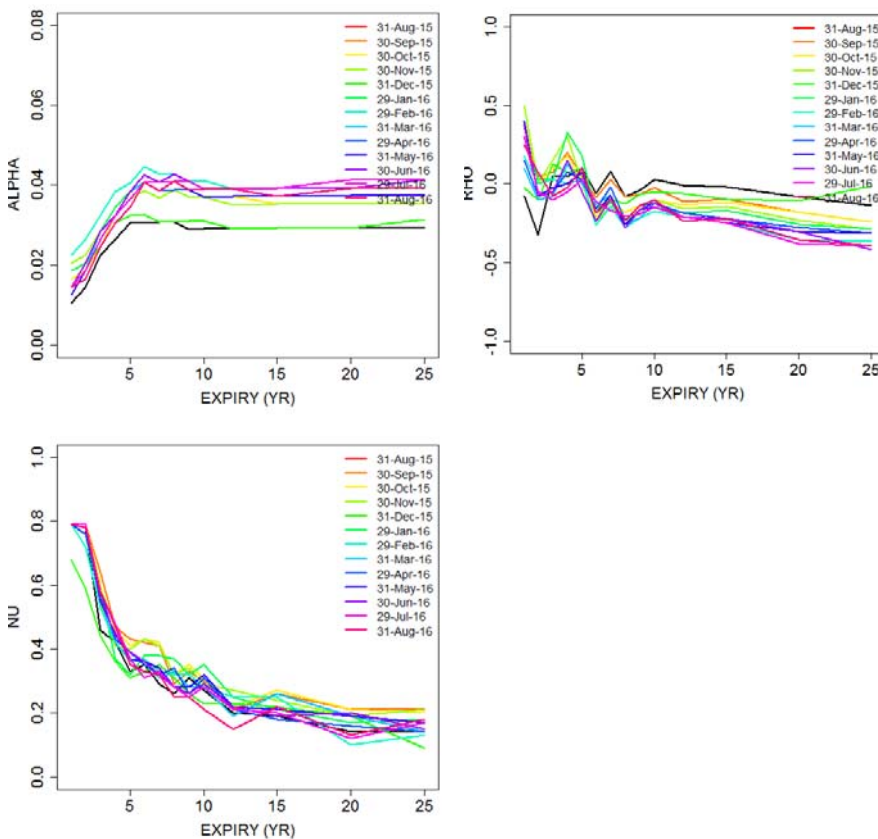
In the figure below we illustrate an example of caplet stripping. This example assumes a flat interpolation and is done on the EUR 6M tenor as of 31 August 2016. The figure shows that differences in caplet vols are not significant and thus we do not expect the flat interpolation assumption to play a big role in the stability of the SABR parameters. The impact on the MTM can be quantified in terms of the Vega sensitivity.



# Stability of SABR parameters

In order to examine the stability of the SABR parameters, we have calibrated the shifted SABR model on the EUR 6M cap market for a series of end-of-month valuation dates, from 31 August 2015 to 31 August 2016. For each of these valuation dates we have obtained the input normal cap vols from Bloomberg for a range of strikes from 1% to 11% (and also including the ATM point) and for a range of maturities from 1YR to 25YR.

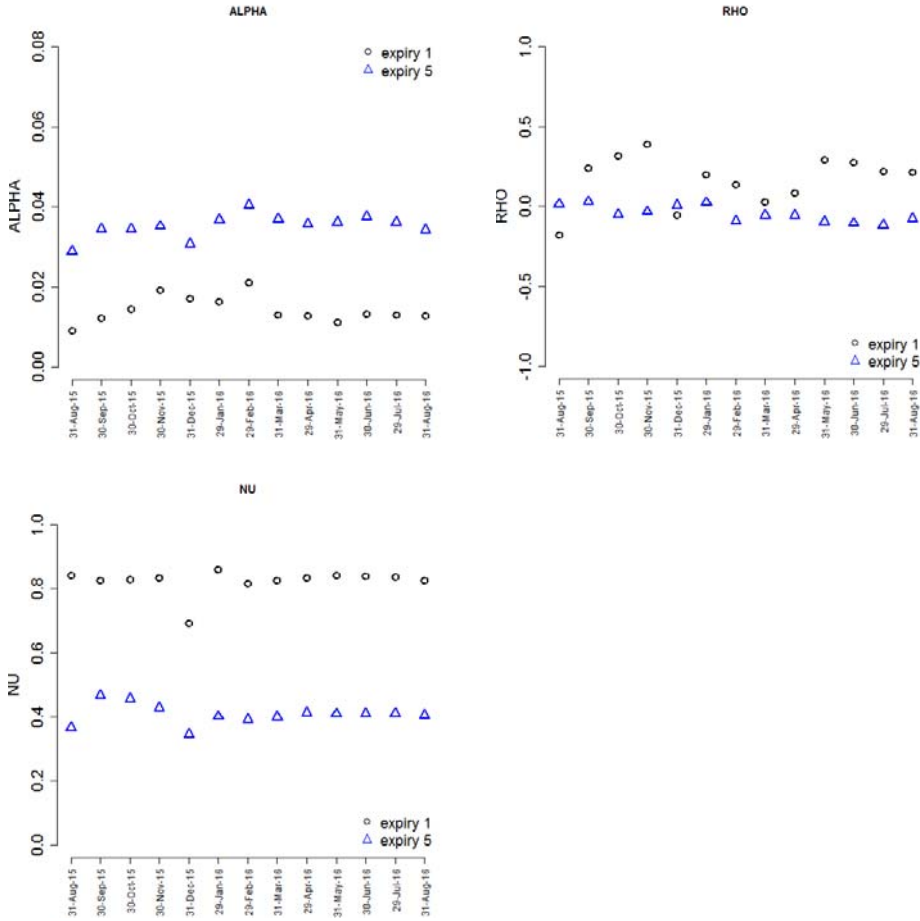
The figures below show the calibrated values of alpha, rho and nu obtained in the shifted Black calibration space with a shift of 2% and a value of beta fixed to 0.5.



The various lines in the figures correspond to calibrations at different valuation dates. These figures show that the values of the three parameters do not fluctuate significantly. Alpha, Rho and Nu each follow a main trending curve.



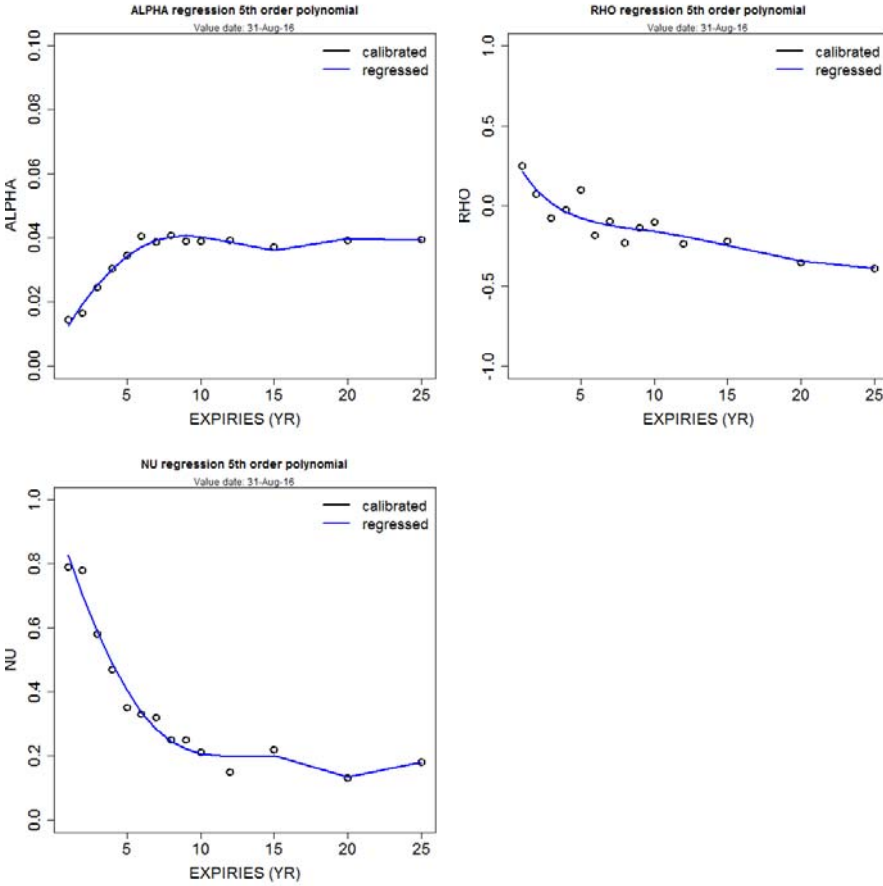
An alternative way to view these results is to isolate certain expiries and plot the values of the parameters against the valuation dates. This can be seen in the figure below:



On the horizontal axis we find the 14 valuation dates and on the vertical axis the value of the SABR parameter for the 1YR and 5YR expiries. From here we see that across valuation dates the deviation is not significant. There are certain isolated instances where the values jump (for example, on the 31 December 2015 valuation) but this may have roots linked to end-of-year closing trades.

In order to smoothen further the calibration results, one could regress the obtained results, either across expiries or across valuation dates. A regression across valuation dates could also be used in order to forecast the values of the SABR parameters at a future valuation date or in order to make an educated guess of the appropriate initial conditions of the optimiser at a future valuation date.

We have applied a linear regression of 5<sup>th</sup> order across the expiries for each of the valuation dates. The particular order of the applied regression is not very important, as long as one does not overfit. The result is shown in the figure below:



With the regression results at hand one would now be tempted to quantify the stability of the SABR parameters by examining how much cap prices would differ using a pricing based on (i) the raw calibrated parameters versus (ii) the regressed parameters. If the SABR model were stable then one would expect that the regressed cap prices would not differ much from the calibrated ones.

The results of this test are shown in the three tables below.

The first table shows the values of cap prices using as valuation date 29 February 2015 (a middle date in the pool). They have been obtained via a simple conversion of the raw Bloomberg cap vols using a Black formula. Hence this can be considered as the reference table.

## CAP PRICES

### BLOOMBERG

Tenor	ATM K	ATM	1.00%	1.50%	2.00%	2.50%	3.00%
1Yr	-0.24%	10,134	15,794	4,207	1,455	0,597	0,278
2Yr	-0.24%	28,171	1,323	709	436	293	210
3Yr	-0.19%	56,001	7,526	4,384	2,814	1,941	1,410
4Yr	-0.11%	97,871	24,683	15,403	10,273	7,230	5,310
5Yr	-0.02%	157,913	56,774	37,272	25,650	18,391	13,663
6Yr	0.09%	236,309	108,035	73,170	51,174	36,954	27,481
7Yr	0.21%	324,995	178,480	124,930	89,698	66,209	50,195
8Yr	0.33%	424,746	267,137	191,078	138,916	103,127	78,270
9Yr	0.44%	529,501	369,584	269,691	199,124	149,605	114,667
10Yr	0.54%	637,762	482,560	358,086	268,318	204,174	158,226

The second and third tables (below) show the cap price values obtained by using the raw calibrated SABR parameters vs the regressed SABR parameters. Taking into account that the notional considered in this test was 10 mio EUR implies that the absolute difference in the cap prices between regressed vs calibrated is a mere 0.85 basis points. This is an acceptable difference.

## CALIBRATED

### SABR

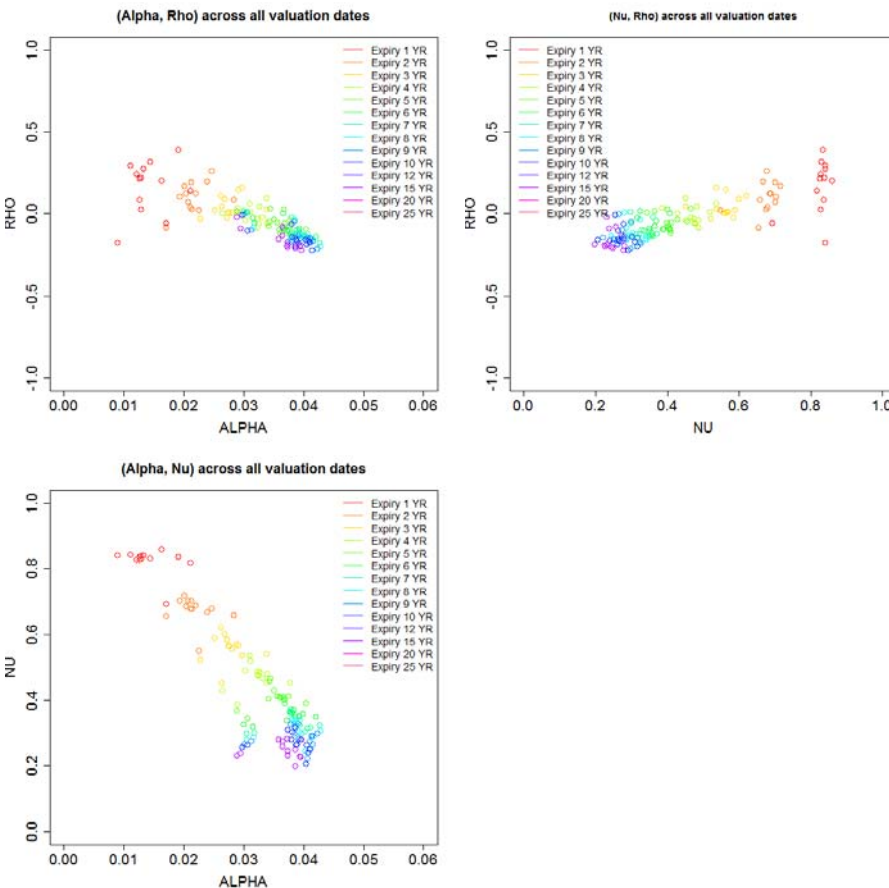
Tenor	ATM K	ATM	1.00%	1.50%	2.00%	2.50%	3.00%
1Yr	-0.24%	10,195	16,591	4,130	1,334	0,514	0,226
2Yr	-0.24%	28,029	1,330	727	452	305	219
3Yr	-0.19%	55,958	7,407	4,361	2,834	1,975	1,447
4Yr	-0.11%	97,378	24,753	15,625	10,520	7,447	5,484
5Yr	-0.02%	157,680	57,149	37,778	26,112	18,756	13,920
6Yr	0.09%	235,448	108,294	73,533	51,436	37,090	27,526
7Yr	0.21%	324,301	178,503	124,938	89,490	65,814	49,697
8Yr	0.33%	424,425	267,962	191,834	139,128	102,736	77,436
9Yr	0.44%	529,564	370,988	271,217	200,066	149,754	114,121
10Yr	0.54%	636,905	483,057	359,234	269,166	204,412	157,899

REGRESSED

SABR

Tenor	ATM K	ATM	1.00%	1.50%	2.00%	2.50%	3.00%
1Yr	-0.24%	9,988	13,802	3,510	1,161	0,459	0,206
2Yr	-0.24%	28,520	1,389	729	435	284	196
3Yr	-0.19%	57,015	8,183	4,865	3,172	2,208	1,615
4Yr	-0.11%	99,462	25,268	15,922	10,752	7,662	5,692
5Yr	-0.02%	159,313	56,370	36,941	25,480	18,361	13,721
6Yr	0.09%	234,096	106,018	71,978	50,658	36,896	27,711
7Yr	0.21%	323,307	177,465	124,501	89,477	65,983	49,897
8Yr	0.33%	422,305	266,779	192,054	140,494	104,786	79,783
9Yr	0.44%	528,115	370,795	272,543	202,482	152,677	117,117
10Yr	0.54%	637,571	484,946	362,325	272,693	207,661	160,483

An alternative way to visualise the co-movement of the three parameters across expiries is to plot them against each other. The figure below shows (alpha,rho), (nu,rho) and (alpha, nu) for all calibrations in the 13 valuation dates. These calibrations have been done on the EUR 6M cap market using the Black asymptotic formula with a shift of 2% and beta=1/2. The various expiries are shown in different colors.



In the left picture we see that optimum solution moves from left (red) to right (magenta). While the optimal solution for the various valuation dates appear somewhat scattered in the first expiries, they settle down to more localised regions towards the final expiries. This is to be expected: the market view for the first expiries is much clearer than that of the last expiries. We also see that as expiry progresses from 1YR to 25YR the alphas tend to increase while the rhos tend to somewhat decrease. This can be appreciated on the basis that alphas are linked to ATM vols while rhos are linked to the skew. As expiry increases, the term-structure of the ATM vols shows an increase while the smile flattens out. At the same time, the second figure shows that the value of the parameter nu decreases. This is indicative of the loss in convexity of the caplet smile, as expiries go from 1YR to 25YR.

# Calibration space

The SABR model expresses the implied volatility either in terms of a Black volatility (which will be input to a Black'76 formula) or in terms of a Normal volatility (which will be input to a Bachelier formula). In recent years, with the interest-rates going into the negative domain there has been an obvious obstacle in any Black pricing engine: the Black formula requires the computation of the logarithm of the forward and of the strike, which, if negative, leads to an unpleasant exception error.

One quick fix to this problem is to shift both the forward and the strike so that the logarithm is not undefined. This then leads to a new model, the *shifted* SABR model. The asymptotic expansions of Hagan et. al. and Berestycki et. al.<sup>2</sup> can easily be adapted in order to deal with this shift. In a Black world, these formulas would no longer yield the common Black volatility, rather, they quote a shifted Black volatility. In the Normal world, the Hagan asymptotic expansion will yield a Normal volatility (note that in the Bachelier formula, the shift on the strike and the shift on the forward will cancel each other out, meaning that there is no impact of a shift on a normal model). Calibration of the SABR model using a shifted Black SABR asymptotic formula would be called the “(shifted) Black calibration space”, whereas a calibration using the Normal asymptotic formula is called the “Normal calibration space”.

## Black Calibration Space

$$\sigma_B(K, f) = \frac{\alpha}{(f\beta)^{\frac{(1-\beta)}{2}} \left\{ 1 + \frac{(1-\beta)^2}{24} \log^2 \frac{f}{K} + \frac{(1-\beta)^4}{1920} \log^4 \frac{f}{K} + \dots \right\}} \cdot \left( \frac{z}{\chi(z)} \right) \cdot \left\{ 1 + \left[ \frac{(1-\beta)^2}{24} \frac{\alpha^2}{(fK)^{1-\beta}} + \frac{1}{4} \frac{\beta\rho\alpha v}{(fK)^{\frac{(1-\beta)}{2}}} + \frac{2-3\rho^2}{24} v^2 \right] \right\} \cdot T + \dots$$

where  $z$  and  $\chi(z)$  are abbreviations of

$$z = \frac{v}{\alpha} (fK)^{\frac{(1-\beta)}{2}} \log \frac{f}{K}$$

$$\chi(z) = \log \left( \frac{\sqrt{1 - 2\rho z + z^2} + z - \rho}{1 - \rho} \right)$$

<sup>2</sup> Hagan et al “Managing Smile Risk” Wilmott Magazine (7/2002) and Berestycki et al. “Computing the implied volatility in stochastic volatility models” Comm. Pure Appl. Math., 57 1352, 2004

## Normal Calibration Space

$$\sigma_N(K, f) = \alpha(fK)^{\frac{\beta}{2}} \frac{1 + \frac{1}{24} \log^2 \frac{f}{K} + \frac{1}{1920} \log^4 \frac{f}{K} + \dots}{1 + \frac{(1-\beta)^2}{24} \log^2 \frac{f}{K} + \frac{(1-\beta)^4}{1920} \log^4 \frac{f}{K} + \dots} \cdot \left( \frac{z}{\chi(z)} \right) \cdot \left\{ 1 + \left[ \frac{-\beta(2-\beta)}{24} \frac{\alpha^2}{(fK)^{1-\beta}} + \frac{1}{4} \frac{\beta \rho \alpha v}{(fK)^{\frac{1-\beta}{2}}} + \frac{2-3\rho^2}{24} v^2 \right] \right\} \cdot T + \dots$$

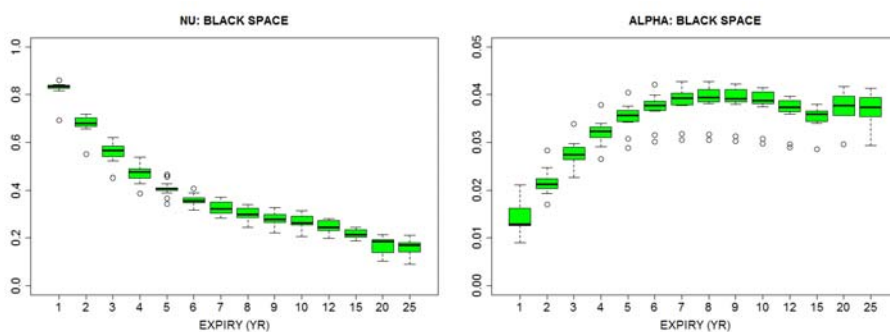
These expressions hold for any value of beta. Notice that a shift is necessary (due to the presence of logarithms of the strike and forward) in either the Black or the Normal calibration space.

The *Hagan et al* article derives in the special case of beta=0 a convenient expression for the normal implied vol<sup>3</sup>. The expression in the Normal beta=0 case contains no logarithms and can thus be used, in the presence of negative strikes or forwards, without the need to introduce a shift. This implies that there is no need for laborious software adaptations apart from fixing the parameter beta to the value of zero, provided the pricing library can already handle a calibration in the beta=0 Normal space.

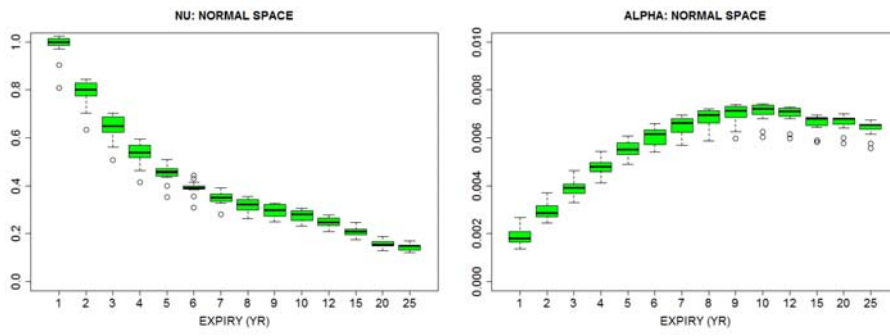
There is a certain amount of discussion in the literature and among market dealers of whether a SABR model with beta=0 would be an appropriate model. This is because setting beta equal to zero in the SABR model would lead to a stochastic differential equation for the forward whereby the increments to the forward rate do not depend on its current value. This is, from a phenomenological point of view, a problematic issue, although, from a pricing point of view, all that matters to a model is its calibration to the observed market prices.

The question that then rises is whether the Normal beta=0 model (without a shift) is as appropriate as the shifted beta>0 model, in terms of stability. In order to provide some indicative answers to this question we have calibrated the pool of EUR6M historical data in both the shifted Black calibration space (with beta=0.5 and shift=2%) and in the Normal calibration space (with beta=0 and shift=0%).

The results are presented in the figures below which show boxplots across all expiries for both calibration spaces. Each of the boxplots contain 50% of the calibration data for all valuation dates for each expiry.



<sup>3</sup> The reader is warned that the normal beta=0 formula in the *Hagan et al* paper contains a typo error.



The thick black line in the boxplot corresponds to the median. The markers (circles) outside the boxplots correspond to outliers. One notices that either of the two calibration spaces leads to approximately similar trends. The calibrated values are well-contained and the outliers are few. This indicates stability in either of the two calibration spaces.



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