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Numerical Accuracy of Real Inversion Formulas for the Laplace Transform

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Abstract: In this paper we investigate and compare a number of real inversion formulas for the Laplace transform. The focus is on the accuracy and applicability of the formulas for numerical inversion. In this contribution, we study the performance of the formulas for measures concentrated on a positive half-line to continue with measures on an arbitrary half-line.

Keywords: Laplace transform, numerical inversion, Post-Widder inversion, Widder inversion, Shohat-Tamarkin formula, Gaver-Stehfest inversion.

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1 Introduction

In this paper we investigate and compare a number of real inversion formulas for the Laplace transform. The focus is on the accuracy and applicability of the formulas for numerical inversion. In this contribution, we study the performance of the formulas for measures concentrated on a positive half-line to continue with measures on an arbitrary half-line.

The remaining of the paper is organised as follows. In Section 2 we formulate the inversion formulas used to recover a measure defined on the positive half-line. Section 3 describes the potential of these formulas for numerical inversion of a probability measure. An extension of these formulas is given in Section 4. We compare the numerical results obtained by the original formulas on the one hand, and their extensions on the other. Section 5 is dedicated to another extension of the original formulas. In particular, we study the performance of the formulas adapted for the case where the measure is concentrated on an arbitrary half-line.

2 Preliminaries

In this section we describe the general framework and give an overview of the original inversion formulas.

Assume that $\mu$ is a bounded measure on the positive half-line. We define its Laplace transform by

$$\hat{\mu}(u) := \int_0^\infty e^{-ux} d\mu(x),$$

where $u \geq 0$. We are interested in recovering $\mu(.)$ from its Laplace transform $\hat{\mu}(.)$. For $0 \leq y_1 < y_2$, denote by $\mu\{y_1; y_2\}$ the inversion of the measure $\mu$ on $[y_1, y_2]$ such that

$$\mu\{y_1; y_2\} = \frac{1}{2} \mu\{y_1\} + \mu(y_1, y_2) + \frac{1}{2} \mu\{y_2\}.$$

Here $\mu\{y\}$ stands for the weight or measure at the point $y$ while $\mu(a, b)$ is shorthand for the measure of the open interval $(a, b)$.

For probabilistic proofs of a number of the inversion formulas used below, we refer to [8]. For ease of reference, we briefly go through these formulas.

2.1 Post-Widder Formula [2, 10]

This is one of the classical inversion formulas and it can be found in [10]. From [8] we have for $0 \leq y_1 < y_2$

$$\mu\{y_1; y_2\} = \lim_{n \to \infty} \int_{y_1}^{y_2} \frac{(-n)^n}{\Gamma(n)} \frac{\hat{\mu}^{(n)}(\frac{n}{t})}{t^{n+1}} \, dt.$$

(1)

Note that in order to recover the measure $\mu$ by the Post-Widder formula, one has to calculate all derivatives of the Laplace transform on the entire positive half-line.
2.2 Widder Formula [10]

From [8] we know that for $0 \leq y_1 < y_2$

$$\mu\{y_1; y_2\} = \lim_{n \to \infty} \sum_{m=[ny_1]+1}^{[ny_2]} \frac{(-n)^m}{m!} \hat{\mu}^{(m)}(n).$$

(2)

It follows from (2) that, in order to invert $\hat{\mu}$, one has to find all derivatives of $\hat{\mu}$ in the variable point $n$, $n \to \infty$.

2.3 Shohat-Tamarkin Formula [6]

For $0 \leq y_1 < y_2$ we have

$$\mu\{y_1; y_2\} = \int_{y_1}^{y_2} \sum_{k=0}^{n} \sum_{r=0}^{k} \frac{n!}{k! (n-k)!} \hat{\mu}^{(k)}(L_n(u)) \, du,$$

(3)

where

$$L_n(u) = \sum_{r=0}^{n} \frac{n}{n-r} \left(\frac{-u}{r!}\right)^r$$

(4)

are the classical Laguerre polynomials. In order to recover the measure $\mu$ by the Shohat-Tamarkin formula, one has to calculate the Laplace transform $\hat{\mu}$ and all its derivatives in the single point 1. In [8] the formula (3) has been generalized in such a way that it requires the Laplace transform and its derivatives at an arbitrary point on the positive half-line.

2.4 Gaver-Stehfest Formula [4, 5]

From [8] we have for $0 \leq y_1 < y_2$

$$\mu\{y_1; y_2\} = \lim_{n \to \infty} \sum_{k=0}^{n} b_{n,k} \left[ \hat{\mu} \left( \frac{n+k}{y_2} \log 2 \right) - \hat{\mu} \left( \frac{n+k}{y_1} \log 2 \right) \right],$$

(5)

where

$$b_{n,k} = \frac{(-1)^n}{(n+k)} \binom{2n}{n} \binom{n}{k}.$$

(6)

It follows from (5) that the inversion requires the Laplace transform $\hat{\mu}$ in two real points but none of its derivatives.

3 Inversion Formulas on the Positive Half-line

As our trial distribution for $\mu$ on the positive half-line, we take Gamma($\alpha, \beta$), $\alpha > 0$, $\beta > 0$, distribution function $F_G(x)$, $x \geq 0$. The density is given by

$$f(x) = \frac{\beta^\alpha}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x}, \ x > 0.$$

We will test the inversion formulas listed above to recover the Gamma cumulative distribution function from its Laplace transform given by

$$\hat{\mu}(u) = \left(1 + \frac{u}{\beta}\right)^{-\alpha}, \ u > 0.$$
The Gamma family provides a rich family of distributions allowing a variety of desirable tail behavior that can be obtained by varying the shape parameter $\alpha$. If we take $\alpha = 1$ then we obtain the exponential distribution that plays a benchmark role. By varying the shape parameter one obtains either heavier tails for $\alpha < 1$ or lighter tails $\alpha > 1$ than the tail of the exponential distribution. We choose the scale parameter $\beta$ equal to $\sqrt{\alpha}$. In this way we reduce the number of parameters to one. In what follows we will refer to the Gamma($\alpha, \sqrt{\alpha}$) distribution as to Gamma($\alpha$).

Consider the four inversion formulas: Post-Widder (P-W, 1), Widder (W, 2), Shohat-Tamarkin (S-T, 3), and Gaver-Stehfest (G-S, 5). We test these formulas for different values of $\alpha$ and on a number of intervals $[y_1, y_2]$, $0 \leq y_1 < y_2 \leq y_{up}$, where $y_{up}$ is chosen such that $F_G(y_{up}) \approx 1$.

More specifically, we calculate the relative errors of the numerical inversion by means of these formulas as these errors are used as the measure of the inversion accuracy. The relative error is calculated as

$$\frac{|(F_G(y_2) - F_G(y_1)) - \mu(y_1; y_2)|}{F_G(y_2) - F_G(y_1)} \cdot 100\%.$$ 

In all the considered inversion formulas we either need to take the limit when $n$ goes to infinity or to calculate an unlimited sum. For the implementation we are forced to take some finite number, say $n = N$. The following range for $N$ is recommended:

- for the Post-Widder formula (1), $70 \leq N \leq 130$;
- for the Widder formula (2) the choice depends strongly on $y_2$ and will be discussed below;
- in the Shohat-Tamarkin formula (3) the upper limit of the first summation is in the range $35 \leq N \leq 65$, the larger the $\alpha$ the larger the $N$.
- for the Graver-Stehfest formula (5), $10 \leq N \leq 25$.

### 3.1 The light tail case $\alpha \geq 1$

For this range of the parameter $\alpha$, the Shohat-Tamarkin inversion formula (3) is almost always the most accurate. In Figures 1–4 we plotted the relative errors of numerical inversion by means of all four formulas on the intervals $[0.01, y_2]$ and $[5, y_2]$ for a number of values of $y_2$ and $\alpha = 0.1 \cdot j$, $j = 1, 2, \ldots, 100$. One can see in Figure 3 (left) that the relative error by the Shohat-Tamarkin formula (3) does not exceed 0.16% when the probability distribution has exponential or lighter than exponential tail ($1 \leq \alpha \leq 10$) and $y_1$ is very close to origin. In this case, the other formulas give lower precision, since the Post-Widder (1), Widder (2), and Gaver-Stehfest (5) formulas show relative errors up to 2.5% ($y_2 = 1; \alpha = 10$), 8% ($y_2 = 1; 6 < \alpha < 9$), and even over 100% ($y_2 = 1; \alpha = 10$) respectively.

The inversion error increases as we increase the value of $y_1$ regardless which of the formulas we take. Nevertheless, the relative accuracy of each formula with respect to the others remains approximately the same. If we take for example $y_1 = 5$ and compare the relative errors of the four formulas then the error by the Shohat-Tamarkin (3) goes up to 25% ($y_2 = 12; 1 < \alpha < 2$), that by the Post-Widder (1) lies below 20%, that by the Widder (2) is up to 30%, and that by the Gaver-Stehfest (5) overshoots 100%. The largest error by Shohat-Tamarkin formula corresponds to the small values of the $\alpha$ that are not integers. If we considered only the integer values, as e.g. in Figure 5, then the relative errors would lie below 1%.
Figure 1: Relative errors on the intervals $[0.01, y_2]$ and $[5, y_2]$. Post-Widder (P-W, 1).

Figure 2: Relative errors on the intervals $[0.01, y_2]$ and $[5, y_2]$. Widder (W, 2).

Figure 3: Relative errors on the intervals $[0.01, y_2]$ and $[5, y_2]$. Shohat-Tamarkin (S-T, 3).

Figure 4: Relative errors on the intervals $[0.01, y_2]$ and $[5, y_2]$. Gaver-Stehfest (G-S, 5).
The Shohat-Tamarkin formula is inferior to the others only in the following two cases:

1. The measure of the interval is approaching one (i.e., \(1 - (F_G(y_2) - F_G(y_1)) < 10^{-5}\)), which corresponds to
   - \(y_1 = 0\) or \(y_1\) is very close to the origin, and
   - \(y_2\) is large enough, the order of magnitude of the \(y_2\) being determined by the value of \(\alpha\) (the larger the \(\alpha\), the smaller the \(y_2\)).

2. \(\alpha\) is small, \(1 < \alpha < 2\), and non-integer. Compare Figure 3 and Figure 5.

![Figure 5: Relative errors on the intervals [0.01, \(y_2\)] and [5, \(y_2\)]; \(\alpha\) is integer. Shohat-Tamarkin (S-T, 3).](image)

In the first case, it is, as a rule, the Post-Widder formula (1) that allows to get the most accurate numerical inversion. Note however that (P-W, 1) is not applicable for \(y_1 = 0\), and in that case (G-S, 5) would be the best choice. Despite the fact that the Shohat-Tamarkin formula yields the other formulas on the intervals whose measure is close to one, it still provides relatively good precision with the largest relative error being less than 1%. Compare this to the largest relative errors by the Post-Widder and Gaver-Stehfest formulas that are equal to 0.3% and 0.4% respectively (see Figure 1 (left) and Figure 4 (left)).

### 3.2 The heavy tail case \(\alpha < 1\)

It turns out that the inversion by (S-T, 3) is no longer recommended. As \(\alpha\) decreases and/or we move the interval \([y_1, y_2]\) to the right, the error becomes very large. For example, the relative error overshoots 100% when \(\alpha = 0.5\) and the formula is applied to invert the measure on the interval \([1, 10]\). Here, again, the Post-Widder approach (2) is, as a rule, the best alternative.

### 3.3 Global comparison

In Table 1 we give the average relative errors of inverting the Gamma(\(\alpha\)) probability distribution function on the compact intervals \([y_1, y_2]\), \(y_1 = 0.01\), \(y_2 = 1 + 0.1 \cdot j\), \(j = 1, 2, \ldots, 110\), by the four formulas and for 11 different values of \(\alpha\). The errors are quoted in per cent. The precision of the Shohat-Tamarkin and Gaver-Stehfest formulas does not depend much on whether or not we take \(y_1 = 0\) or \(y_1 = 0.01\). The precision of the Widder approach however does depend on this fact as on average it gives better accuracy when the origin is not included. The Post-Widder approach, as already mentioned, cannot be tested for \(y_1 = 0\). Taking this into account we calculated the average errors on the intervals that start at 0.01 and let \(y_2\) go from 1 to 12. As mentioned
before, the Shohat-Tamarkin formula may perform differently for values of \( \alpha \), integral or not. Compare, for example, the relative errors for \( \alpha = 1; 1.3; 1.8; 2; 2.1 \) in Table 1.

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>0.05</th>
<th>0.5</th>
<th>1</th>
<th>1.3</th>
<th>1.8</th>
<th>2</th>
<th>2.1</th>
<th>4</th>
<th>5.5</th>
<th>7</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-W</td>
<td>0.33</td>
<td>0.05</td>
<td>0.12</td>
<td>0.14</td>
<td>0.18</td>
<td>0.18</td>
<td>0.19</td>
<td>0.22</td>
<td>0.24</td>
<td>0.29</td>
<td>0.47</td>
</tr>
<tr>
<td>W</td>
<td>12</td>
<td>7.2</td>
<td>2.8</td>
<td>1.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>S-T</td>
<td>170</td>
<td>4</td>
<td>8 \times 10^{-9}</td>
<td>0.09</td>
<td>0.016</td>
<td>2 \times 10^{-7}</td>
<td>4 \times 10^{-3}</td>
<td>4 \times 10^{-5}</td>
<td>7 \times 10^{-4}</td>
<td>3 \times 10^{-4}</td>
<td>2 \times 10^{-3}</td>
</tr>
<tr>
<td>G-S</td>
<td>0.4</td>
<td>0.27</td>
<td>0.23</td>
<td>0.18</td>
<td>0.22</td>
<td>0.27</td>
<td>0.32</td>
<td>0.8</td>
<td>1.8</td>
<td>2.4</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Table 1: Average relative errors of inversion formulas on compact intervals \([0, y_2]\), \(1 \leq y_2 \leq 12\), for given \( \alpha \).

Table 2 presents the average by \( \alpha \) relative errors of inverting the same probability measure on 10 different intervals. Averaging is done over the values \( \alpha = 0.05 + 0.3 \cdot j, j = 0, 1, \ldots, 30 \). As the performance of the Shohat-Tamarkin and Gaver-Stehfest formulas depends significantly on whether or not the tail of the distribution to invert is heavier than exponential, we give the average relative errors on compact intervals for \( \alpha > 1 \) and \( \alpha < 1 \) separately in Tables 3 and 4.

**Table 2:** Average relative errors of inversion formulas on given compact interval, \( 0 < \alpha < 10 \).

<table>
<thead>
<tr>
<th>Interval</th>
<th>([0, 0.5])</th>
<th>([0, 1])</th>
<th>([0, 2.5])</th>
<th>([0, 4.9])</th>
<th>([0, 7.5])</th>
<th>([0, 9])</th>
<th>([0, 12.5])</th>
<th>([1, 5.5])</th>
<th>([2.5, 7.5])</th>
<th>([5, 9])</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3</td>
<td>1.2</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>16.4</td>
<td>6.5</td>
<td>3.7</td>
<td>4.1</td>
<td>4.3</td>
<td>4.5</td>
<td>4.9</td>
<td>1.6</td>
<td>0.8</td>
<td>17.5</td>
</tr>
<tr>
<td>S-T</td>
<td>0.07</td>
<td>0.05</td>
<td>0.02</td>
<td>0.18</td>
<td>0.64</td>
<td>0.68</td>
<td>14</td>
<td>0.2</td>
<td>0.5</td>
<td>4.7</td>
</tr>
<tr>
<td>G-S</td>
<td>78</td>
<td>39</td>
<td>3.2</td>
<td>1</td>
<td>0.2</td>
<td>0.06</td>
<td>0.01</td>
<td>2.3</td>
<td>2.8</td>
<td>52</td>
</tr>
</tbody>
</table>

Table 3: Average relative errors of Shohat-Tamarkin and Gaver-Stehfest inversion formulas on given compact interval, \( \alpha < 1 \).

We consider now each of the formulas separately and point out their pros and cons.

**Post-Widder formula.** The formula can be recommended for small values of \( \alpha \), \( 0 < \alpha < 2 \), especially when \( y_1 \) is close (but not equal) to 0. Then the relative error does not exceed 0.4%. It is often possible to obtain a higher precision by choosing larger \( N \), however the upper limit
for $N$ is 143 for computer (Matlab) implementations.

**Widder formula.** This formula can be recommended

- to invert a distribution with very light tail, $\alpha \geq 10$, on the $[0, y_2]$ where $y_2$ is large, e.g. $y_2 \geq 10$; the relative error is then in the range of $[10^{-6}\% , 10^{-4}\%]$; in this case the estimates are obtained with small values of $N$ such as $8 \leq N \leq 16$;

- to invert a heavy-tailed distribution, $\alpha < 0.5$, on short intervals to the right from the mean, the relative error being less than 1%; here $N \geq 20$.

In general, the choice of $N$ depends on $y_2$ (the larger the $y_2$ the smaller the $N$); this is caused by the limited capacity of the computer to manage factorials of the kind $[N \cdot y_2]!$ appearing in the summation. As in the Post-Widder case, the maximal possible value of $N$ is 143.

For $\alpha < 2$ the formula exhibits different behavior depending on whether or not the value of 0 is included in the interval. In Figure 6 one can see that the error may be reduced if we exclude zero; this fact holds for $\alpha < 2$ and all values of $y_2$. However from $\alpha \geq 2$ the estimates become undistinguishable.

**Shohat-Tamarkin formula.** The formula provides the best inversion in the majority of the considered cases. If we invert the Gamma($\alpha$) distribution function on a fixed interval $[y_1, y_2]$, then the error tends to increase as the Gamma parameter $\alpha$ increases, however the error growth is not monotone. In particular, the accuracy for integer values of $\alpha$ is typically higher than for non-integer values. For a fixed $y_2$, the error increases as $y_1$ increases, and this holds for all $\alpha$.

---

<table>
<thead>
<tr>
<th>Interval</th>
<th>$[0, 0.5]$</th>
<th>$[0, 1]$</th>
<th>$[0, 2.5]$</th>
<th>$[0, 4.9]$</th>
<th>$[0, 7.5]$</th>
<th>$[0, 9]$</th>
<th>$[0, 12.5]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-T</td>
<td>0.057</td>
<td>$6 \cdot 10^{-4}$</td>
<td>$3 \cdot 10^{-4}$</td>
<td>$6 \cdot 10^{-4}$</td>
<td>$1.4 \cdot 10^{-3}$</td>
<td>0.02</td>
<td>0.62</td>
</tr>
<tr>
<td>G-S</td>
<td>80</td>
<td>40</td>
<td>3.4</td>
<td>1.3</td>
<td>0.22</td>
<td>0.07</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Table 4: Average relative errors of Shohat-Tamarkin and Gaver-Stehfest inversion formulas on given compact interval, $\alpha > 1$.
For fixed $y_1$ and $\alpha$, the error increases as the values of $y_2$ become larger.

**Gaver-Stehfest formula.** Similar to the Post-Widder approach (1), the Gaver-Stehfest formula allows to obtain rather precise inversion for any value of $\alpha$ when $y_1$ and $y_2$ are such that $1 - (F_G(y_2) - F_G(y_1)) < 10^{-5}$. This is the case, for example, when $y_1$ is close to the origin while $y_2$ is large. The formula performs better when the distribution has a heavier than exponential tail, i.e. when $\alpha < 1$. However, in both cases one can obtain a higher accuracy of inversion using the Post-Widder approach when $y_1 > 0$. Therefore, the Gaver-Stehfest is only sensibly applicable when $y_1 = 0$.

For a fixed $y_2$, the error by Gaver-Stehfest increases as $y_1$ increases; this holds for any value of $\alpha$. For a fixed $y_1$, the error decreases as we increase the length of the interval. However, the error as a function of $\alpha$ is again not monotone.

### 4 Refined Formulas

Let $\mu$ be a probability measure on $[0, \infty)$. Introduce the **integrated tail** of $\mu$ by the expression

$$
\mu_1(y) := \int_0^y (1 - \mu(x)) \, dx.
$$

Then its Laplace transform is given by

$$
\hat{\mu}_1(s) = s^{-1}(1 - \hat{\mu}(s)).
$$

It is quite clear that the integral formulas given in Section 2 have a special version in the case when the measure $\mu$ has a derivative. For example, the Post-Widder case leads to

$$
\frac{d\mu(y)}{dy} = \lim_{n \to \infty} \frac{(-n)^n}{\Gamma(n)} \mu(n) \left( \frac{n}{y} \right)^{1/n+1}.
$$

But then these density formulas can be applied to recover the measure $\mu$ from the Laplace transform of $\mu_1$. This then leads to a direct formula for the measure $\mu$. Applying this procedure to the integral inversion formulas among (1)–(5) we obtain some refinements.

**Post-Widder formula.** From (1) for $y \geq 0$ we have

$$
\mu(y) = \lim_{n \to \infty} \sum_{\ell=0}^n \frac{1}{\ell!} \left( \frac{n}{y} \right)^\ell \hat{\mu}^{(\ell)} \left( \frac{n}{y} \right).
$$

The latter formula has been discovered by Stadtmüller-Trautner in [7]. See also [8].

One can hardly compare the performance of the newly introduced formula to the original one because it inverts intervals starting at 0 while the original does not. Table 5 shows the average by $\alpha$ relative errors of inverting Gamma($\alpha$) probability function on the same intervals as in Table 2. One can immediately see that the refined Post-Widder formula outperforms all the others on large intervals and yields only to Shohat-Tamarkin on small intervals.

**Shohat-Tamarkin formula.** Starting from (3) we obtain for $y \geq 0$

$$
1 - \mu(y) = 1 - \hat{\mu}(1) - \sum_{\ell=1}^\infty \frac{\hat{\mu}^{(\ell)}(1)}{\ell!} \sum_{n=0}^\infty \left( \sum_{k=\ell}^n (-1)^{k-\ell} \binom{n}{k} \sum_{k=0}^n \binom{n}{k} \frac{(-y)^k}{k!} \right).
$$

(9)
We apply expression (9) to numerically recover \(1 - F_G(y)\) from its Laplace Transform, and compare the results to the inversion of \(\mu \{ y, \infty \}\) by the original Shohat-Tamarkin approach (3).

The newly introduced formula allows to improve the precision of the numerical inversion for \(0 < \alpha < 1\), especially in the tail. The errors are further reduced at least by factor 3 (see Figure 7). As we increase \(\alpha\), say \(1 < \alpha < 3\), the accuracy of (9) remains still higher than that of (3) for \(y > 6\), whereas it is lower closer to the origin (see Figure 8(a)). For \(\alpha > 3\), however the initial formula (3) works better (see Figure 8(b)).

**Gaver-Stehfest formula.** Let \(\mu\) come from a probability measure without mass at the origin, then its Laplace transform takes on the values \(0 = \hat{\mu}(\infty)\) and \(1 = \hat{\mu}(0)\). We can take \(y_2 = \infty\) in (5) to get the Gaver-Stehfest inversion formulas for the tail

\[
1 - \mu(y) = \lim_{n \to \infty} \sum_{k=0}^{n} b_{n,k} \left[ 1 - \hat{\mu} \left( \frac{n + k}{y} \log 2 \right) \right], \quad y \geq 0, \tag{10}
\]

where \(b_{n,k}\) as defined in (6).

Alternatively we can take \(y_1 = 0\) to get another version of this formula

\[
\mu(y) = \lim_{n \to \infty} \sum_{k=0}^{n} b_{n,k} \cdot \hat{\mu} \left( \frac{n + k}{y} \log 2 \right), \quad y \geq 0. \tag{11}
\]

For given \(y\) and \(n\) both (10) and (11) provide, obviously, the same value. However, formula (11) allows in average to get more exact approximations of \(\mu(y)\) due to another choice of \(n\). The accuracy by formula (11) is slightly lower for \(0 < \alpha < 1.25\) and significantly higher for \(\alpha > 1.25\) than the accuracy by (10). In Figure 9(a) we plotted the Gamma(6.05) tail, \(1 - F_G(y)\), together with its approximation by (8), (9), (10), and (11). The solid line corresponds to the approximation by formula (10) while the dash-dot line to the approximation by (11). One can immediately see that formula (11) provides higher accuracy than its counterpart (10) when \(3 < y < 6\).

As in the former discussion for a compact interval, the refined Shohat-Tamarkin formula remains less accurate when \(\alpha < 1\) (see e.g. Figure 9(b)).

### 5 Inversion Formulas on an Arbitrary Half-line

Let us now allow the measure to be spread over a half-line that is not necessarily the positive real line. Assume that \(\nu\) is a bounded measure concentrated on the interval \([-a, \infty)\) where we

<table>
<thead>
<tr>
<th>Interval</th>
<th>[0, 0.5]</th>
<th>[0, 1]</th>
<th>[0, 2.5]</th>
<th>[0, 4.9]</th>
<th>[0, 7.5]</th>
<th>[0, 9]</th>
<th>[0, 12.5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-W</td>
<td>7.8</td>
<td>3</td>
<td>0.8</td>
<td>0.25</td>
<td>0.02</td>
<td>0.002</td>
<td>10^{-4}</td>
</tr>
</tbody>
</table>

Table 5: Average relative errors of the refined Post-Widder (P-W, 8) inversion formula on given compact interval, \(0 < \alpha < 10\).
Relative errors. Original and refined Shohat–Tamarkin
(a) Relative errors, $\alpha = 0.55$

(b) Difference in relative errors, $\alpha = 0.55$

Figure 7: Original (S-T, 3) vs refined (S-T, 9) Shohat-Tamarkin formulas, $0 < \alpha < 1$

Relative errors. Original and refined Shohat–Tamarkin
(a) $1 < \alpha < 3$

(b) $\alpha \geq 3$

Figure 8: Original (S-T, 3) vs refined (S-T, 9) Shohat-Tamarkin formulas, $\alpha > 1$.

Tail of the Gamma(6.05) distribution
(a) $\alpha = 6.05$

Tail of the Gamma(0.05) distribution
(b) $\alpha < 1$

Figure 9: Post-Wider, (P-W, 8), Shohat-Tamarkin (S-T, 9), and Gaver-Stehfest (G-S, 10) and (G-S, 11) refined formulas
suppose that \( a \geq 0 \). The Laplace transform is then given by
\[
\hat{\nu}(u) := \int_{-a}^{\infty} e^{-ux} \, d\nu(x) = e^{au} \int_{0}^{\infty} e^{-uy} \mu(dy) =: e^{au} \hat{\mu}(u),
\]
where
\[
\mu(dy) := \nu(-a + dy),
\]
is a measure concentrated on the non-negative real line. We can recover the measure \( \nu(\cdot) \) once we know the Laplace transform \( \hat{\mu}(\cdot) \). Following the notations introduced in Section 2, the measure \( \nu \) on \([-\omega_1, \omega_2], -a \leq \omega_1 < \omega_2 \), is given by
\[
\nu\{\omega_1; \omega_2\} = \mu\{a + \omega_1; a + \omega_2\}. \tag{13}
\]
Now we can apply any inversion formula on a compact interval to the right-hand side of (13).

5.1 Post-Widder Formula
From [8] we have for \(-a \leq \omega_1 < \omega_2\)
\[
\nu\{\omega_1; \omega_2\} = \lim_{n \to \infty} \int_{\omega_1}^{\omega_2} \frac{(-n)^n}{\Gamma(n)} \hat{\mu}^{(n)}(n) \frac{n}{a + v} \frac{dv}{(a + v)^{n+1}}. \tag{14}
\]
The link between the derivatives of \( \hat{\mu} \) and those of \( \hat{\nu} \) is given by the following expression
\[
\hat{\mu}^{(k)}(u) = e^{-au} \sum_{\ell=0}^{k} \frac{k!}{\ell!} (-a)^{k-\ell} \hat{\nu}^{(\ell)}(u) \tag{15}
\]
that can be obtained from (12) by applying Leibniz’s differentiation formula.

5.2 Widder Formula
From [8] we have for \(-a < \omega\)
\[
\nu\{-a; \omega\} = \lim_{n \to -\infty} \sum_{\ell=0}^{[n(a+\omega)]} \frac{(-n)^\ell}{\ell!} \hat{\mu}^{(\ell)}(n) \sum_{r=0}^{[n(\omega+a)]-\ell} e^{-an} \frac{(an)^r}{r!}. \tag{16}
\]

5.3 Shohat-Tamarkin Formula
The extension of the Shohat-Tamarkin formula (3) for \(-a \leq \omega_1 < \omega_2\) is
\[
\nu\{\omega_1; \omega_2\} = \int_{\omega_1}^{\omega_2} \sum_{n=0}^{\infty} \frac{\hat{\mu}(n)(1)}{n!} t_n(a, v) \, dv, \tag{17}
\]
where
\[
t_n(a, v) = \sum_{m=0}^{\infty} e^{-a} \frac{(-a)^m c_{n+m}(a + v)}{m! \frac{(n + m)!}{(n + m)}},
\]
and where in turn
\[
c_k(u) = \sum_{n=k}^{\infty} \frac{n!}{(n-k)!} L_n(u),
\]
with \( L_n(u) \) as defined in (4).
For numerical implementation it is convenient to rearrange the terms in the right-hand side of (17) in such a way that there remains only one unlimited sum:

\[
ν\{ω_1; ω_2\} = \int_{ω_1}^{ω_2} \sum_{ℓ=0}^{∞} \sum_{n=0}^{ℓ} \frac{ℓ! \hat{μ}^{(n)}(u)}{n!} L_n(a + v) \sum_{m=0}^{ℓ-n} e^{-a} \left(\frac{(-a)^m}{m!(n + m)! (ℓ - n - m)!}\right) dv.
\]

5.4 Gaver-Stehfest Formula

We have for \(-a ≤ ω_1 < ω_2\)

\[
ν\{ω_1; ω_2\} = \lim_{n→∞} \sum_{k=0}^{n} b_{n,k} \left[ 2^{-\frac{a(n+k)}{a+ω_2}} ν \left(\frac{n + k}{a + ω_2} \log 2\right) - 2^{-\frac{a(n+k)}{a+ω_1}} ν \left(\frac{n + k}{a + ω_1} \log 2\right) \right],
\]

where \(b_{n,k}\) has been defined in (6).

5.5 Stadtmüller-Trautner Formula [7]

If \(ν(x)\) is a probability measure on \([-a, ∞)\) then for \(-a < x\) we have

\[
ν(x) = \lim_{n→∞} \sum_{m=0}^{n} \frac{\hat{μ}^{(m)}(x)}{m!} \left(-\frac{n}{x}\right)^m \sum_{r=0}^{n-m} e^{-\frac{na}{x}} \left(\frac{na}{x}\right)^r r!.
\]

5.6 Numerical Results

As an example of a bounded measure on \([-a, ∞), a ≥ 0\), we take the shifted Gamma(α) distribution whose Laplace transform is

\[
ν(u) = e^{-au} \hat{μ}(u) = e^{au} \cdot \left(1 + \frac{u}{\sqrt{α}}\right)^{-α},
\]

where \(\hat{μ}\) is the Laplace transform of the Gamma distribution as defined in (7). Then the derivatives of \(\hat{μ}\) can be calculated as

\[
\hat{μ}^{(k)}(u) = e^{-au} \sum_{l=0}^{k} \binom{k}{l} (-a)^{k-l} ν^{(l)}(u) = e^{-au} \sum_{j=0}^{l} \binom{l}{j} \left(1 + \frac{u}{\sqrt{α}}\right)^{-α} (j).
\]

We invert the Laplace transform on the intervals \([ω_1, ω_2]\), where \(-a ≤ ω_1 < ω_2\). There are two formulas, the Shohat-Tamarkin and Gaver-Stehfest, that can be used not only for \(-a = ω_1\) but also for \(-a < ω_1\). Both of them, however, provide higher accuracy when \(ω_1 = -a\). We illustrate this in Figures 10(a) and 10(b) where we plotted the absolute errors of the Shohat-Tamarkin and Gaver-Stehfest numerical inversion on \([ω_1, ω_2]\) for the fixed \(ω_1 = -9\), varying \(ω_2 = -8.5, -8, . . . , 2\), two different values of \(a\): \(a = -ω_1 = 9\) and \(a = 12 > -ω_1\). One can see on the graph that the errors are significantly larger when \(ω_1 > -a\). It implies that it is preferable to take \(a = -ω_1\) in order to recover a (probability) measure on the interval \([ω_1, ω_2]\).

As was the case for \(a = 0\), the Post-Widder formula (14) it is not applicable for \(ω_1 = -a\), in analogy to (1) where it was not applicable for \(y_1 = 0\). Taking this into account, the inversion
The relative errors of the inversion for the fixed $\omega_1 = -9$ and two values of $a$: $a = 9.01 \approx -\omega_1$ and $a = 12 > -\omega_1$ are plotted in Figure 10(c). The inversion with $a \approx -\omega_1$ is obviously more accurate.

The Widder formula (16) is derived for $a = -\omega_1$ only. In Figure 10(d) we plot the relative errors of recovering the probability measure for different values of $\alpha$. Clearly, the accuracy decreases as $\alpha$ decreases.

Finally, we study the performance of the inversion formulas for varying $a$. We take $\omega_1 = -a$ for convenience. We illustrate how the increase of $a$ influences the precision of the formulas by taking three arbitrary values of $a$, say $a = 0$, $a = 5$, and $a = 9$, and comparing the corresponding inversion errors. For the Shohat-Tamarkin formula, the dependency of the precision on the value of $a$ is obvious (see Figure 11(a)) while for the other formulas it is not so clear. As seen in Figure 11, larger errors correspond typically to the larger values of $a$, but there are also exceptions. In particular, one can see in Figure 11(e) that the errors by Gaver-Stehfest formula are of the same order of magnitude for the three considered values of the parameter $a$. 

Figure 10: Absolute errors depending on whether $\omega_1 = -a$ or $\omega_1 > -a$. 

by (14) is done on $(-a, \omega_2]$. The relative errors of the inversion for the fixed $\omega_1 = -9$ and two values of $a$: $a = 9.01 \approx -\omega_1$ and $a = 12 > -\omega_1$ are plotted in Figure 10(c). The inversion with $a \approx -\omega_1$ is obviously more accurate.
Figure 11: Dependence of the inversion errors on the value of $a$. 
6 Inversion of measures in the entire real line

It seems tempting to adapt the above procedures to the case where the measure $\mu$ is no longer restricted to a half-line, i.e. when

$$\hat{\mu}(u) := \int_{-\infty}^{\infty} e^{-ux} d\mu(x).$$

However, a number of comments need to be made.

- None of the given procedures seems adaptable for application on the entire real line. In principle one could imagine that it should be possible to let $a$ tend to $\infty$ in the formulas of Section 5. For an early example of such an approach, see [3].

- An alternative would be to find direct formulas that immediately apply to inversion for measures on the entire real line. An example of this kind has been recently derived by Yabukovich [9]. However, a number of numerical experiments suggest that the approximations show very large errors.

- It is well known that the $\hat{\mu}(s)$ exists only in a strip $(\sigma_-, \sigma_+)$ where the value of $\sigma_-$ $(\sigma_+)$ depends on the exponential decay of the right (left) tail of the measure $\mu$. In many practical cases both quantities will be finite implying that one needs to look for inversion formulas that only use the function $\hat{\mu}(u)$ in values of $u$ that satisfy $\sigma_- < \Re u < \sigma_+$. This simple observation suggests that only a potential formula of the Shohat-Tamarkin type is feasible.

It remains a challenging problem to construct accurate real inversion formulas for the two-sided Laplace transform.

7 Conclusions

In the above we have compared the performance of a number of real inversion formulas for the Laplace transform of measures concentrated on a half-line. Overall, the inversion by the Shohat-Tamarkin formula seems to perform best for compact intervals while the Post-Widder and Gaver-Stehfest are preferable for the tail behavior. We have not compared the used inversion formulas with other common inversion techniques that apply approximations by functions of a special type. For a survey of the latter we refer to [1].

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References


