

Pacific Journal of Mathematics

THE INVERSE OF THE ERROR FUNCTION

L. CARLITZ

THE INVERSE OF THE ERROR FUNCTION

L. CARLITZ

1. **Introduction.** In a recent paper [3] J. R. Philip has discussed some properties of the function $\operatorname{inverfc} \theta$ defined by means of

$$(1.1) \quad \theta = \operatorname{erfc}(\operatorname{inverfc} \theta).$$

Since

$$(1.2) \quad \frac{1}{2}\pi^{1/2}(1 - \operatorname{erfc} x) = x - \frac{x^3}{3} + \frac{x^5}{2!5} - \frac{x^7}{3!7} + \frac{x^9}{4!9} \dots$$

it follows that

$$(1.3) \quad \operatorname{inverfc} \theta = u + \frac{1}{3}u^3 + \frac{7}{30}u^5 + \frac{127}{630}u^7 + \frac{4369}{22680}u^9 + \dots,$$

where

$$u = \frac{1}{2}\pi^{1/2}(1 - \theta).$$

The coefficients in (1.3) are rational numbers. It is therefore of some interest to look for arithmetic properties of these numbers.

It will be convenient to change the notation slightly. Put

$$(1.4) \quad f(x) = \int_0^{\infty e^{-t^2/2}} dt,$$

so that

$$f(x) = \left(\frac{\pi}{2}\right)^{1/2} (1 - \operatorname{erfc} 2^{1/2}x)$$

and let $g(x)$ denote the inverse function:

$$(1.5) \quad f(g(u)) = g(f(u)) = u,$$

where

$$(1.6) \quad g(u) = \sum_{n=0}^{\infty} A_{2n+1} \frac{u^{2n+1}}{(2n+1)!} \quad (A_1 = 1).$$

It follows from (1.4) and (1.5) that

$$(1.7) \quad g'(u) = \exp\left(\frac{1}{2}g^2(u)\right).$$

Differentiating again, we get

Received April 11, 1962.

Supported in part by National Science Foundation grants G16485, G14636.

$$(1.8) \quad g''(u) = g(u)(g'(u))^2 .$$

It follows from (1.6) and (1.8) that

$$(1.9) \quad A_{2n+3} = \sum_{r+s \leq n} \frac{(2n+1)!}{(2r)!(2s)!(2n-2r-2s+1)!} A_{2r+1} A_{2s+1} A_{2n-2r-2s+1} .$$

Since $A_1 = 1$ it is evident from (1.9) that all the coefficients A_{2n+1} are positive integers. It is easily verified that the first few values of A_{2n+1} are

$$A_1 = A_3 = 1, \quad A_5 = 7, \quad A_7 = 127, \quad A_9 = 4369 = 17.257 .$$

We shall show that

$$(1.10) \quad A_{2n+p} \equiv -2.4.6 \cdots (p-1) A_{2n+1} \pmod{p} ,$$

where p is an arbitrary prime and that

$$(1.11) \quad A_{2n+5} \equiv -A_{2n+1} \pmod{8}$$

and indeed

$$(1.12) \quad A_{2n+9} \equiv A_{2n+1} \pmod{16} .$$

We also find certain congruences (mod p) for a sequence of integers e_{2n} related to the A_{2n+1} (see Theorems 2 and 3 below).

Finally we put

$$\frac{u}{g(u)} = \sum_0^\infty \beta_{2n} \frac{u^{2n}}{(2n)!}$$

and obtain a theorem of the Staudt-Clausen type for the β_{2n} , namely

$$\beta_{2n} = G_{2n} - \frac{b}{3} - \sum_{p-1/2n} \frac{1}{p} A_p^{2n/(p-1)} ,$$

where G_{2n} is an integer, $b = 2$ or 1 according as $n \equiv 1$ or $\not\equiv 1 \pmod{3}$ and the summation is over all primes $p > 3$ such that $p - 1/2n$. Moreover

$$A_p \equiv -2.4.6 \cdots (p-1) \pmod{p} .$$

2. A series of the form [2]

$$(2.1) \quad H(x) = \sum_{n=0}^\infty a_n \frac{x^n}{n!} ,$$

where the a_n are rational integers, is called a Hurwitz series, or briefly an H -series. It is easily verified that sum, difference and product of two H -series is again an H -series. Also the derivative

and the definite integral of the H -series define by (2.1):

$$H'(x) = \sum_{n=0}^{\infty} a_{n+1} \frac{x^n}{n!}, \quad \int_0^x H(t)dt = \sum_{n=1}^{\infty} a_{n-1} \frac{x^n}{n!}$$

are H -series. If $H_1(x)$ denotes an H -series without constant term then $H_1^k(x)/k!$ is an H -series for $k = 1, 2, 3, \dots$; it follows that $H(H_1(x))$ is an H -series, where $H(x)$ is an arbitrary series of the form (2.1).

By the statement

$$\sum_{n=0}^{\infty} a_n \frac{x^n}{n!} \equiv \sum_{n=0}^{\infty} b_n \frac{x^n}{n!} \pmod{m},$$

where the a_n, b_n are integers, is meant the system of congruences

$$a_n \equiv b_n \pmod{m} \quad (n = 0, 1, 2, \dots).$$

Thus the above statement about $H_1^k(x)/k!$ can be written in the form

$$(2.2) \quad H_1^k(x) \equiv 0 \pmod{k!}.$$

Returning to (1.4) it is evident that

$$(2.3) \quad f(x) = \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n+1}}{2^n(2n+1)n!} = \sum_{n=0}^{\infty} c_{2n+1} \frac{x^{2n+1}}{(2n+1)!},$$

where

$$(2.4) \quad c_{2n+1} = (-1)^n \frac{(2n)!}{2^n n!} = (-1)^n 1 \cdot 3 \cdot 5 \cdots (2n-1),$$

so that $f(x)$ is an H -series without constant term.

If p is an odd prime, it follows from (2.4) that

$$(2.5) \quad c_{2n+1} \equiv 0, \pmod{p} \quad (2n+1 > p).$$

Thus (1.5) implies

$$(2.6) \quad \sum_{n=0}^{1/2(p-1)} c_{2n+1} \frac{g^{2n+1}(u)}{(2n+1)!} \equiv u \pmod{p}.$$

We now compute the coefficient of $u^p/p!$ in the left member of (2.6). Clearly the terms with $1 \leq n < (p-1)/2$ contribute nothing. Hence (2.6) yields

$$A_p + c_p \equiv 0 \pmod{p}.$$

Using (2.4) this becomes

$$(2.7) \quad A_p \equiv -(-1)^m 1 \cdot 3 \cdot 5 \cdots (p-2) \pmod{p},$$

or if we prefer

$$(2.8) \quad A_p \equiv -2 \cdot 4 \cdot 6 \cdots 2m \equiv -\left(\frac{2}{p}\right)m! \pmod{p},$$

where $p = 2m + 1$ and $(2/p)$ is the Legendre symbol. For example we have

$$\begin{aligned} A_5 &\equiv -1 \cdot 3 \equiv 2 \pmod{5}, \\ A_7 &\equiv 1 \cdot 3 \cdot 5 \equiv 1 \pmod{7}, \\ A_{11} &\equiv 1 \cdot 3 \cdot 5 \cdot 7 \cdot 9 \equiv -1 \pmod{11}. \end{aligned}$$

We consider next the residue $(\text{mod } p)$ of A_{p+2n} . If $2n < p$ we have

$$\frac{(p + 2n)!}{(2r)! (2s)! (p + 2n - 2r - 2s)!} \equiv \frac{(2n)!}{(2r)! (2s)! (2n - 2r - 2s)!} \pmod{p}$$

by a familiar property of multinomial coefficients. Thus (1.9) implies (for $2n < p$)

$$(2.9) \quad A_{p+2n+2} \equiv \sum_{r+s \leq n} \frac{(2n)!}{(2r)! (2s)! (2n - 2r - 2s)!} \cdot A_{2r+1} A_{2s+1} A_{p+2n-2r-2s} \pmod{p}.$$

Since $A_p \not\equiv 0 \pmod{p}$ we may put

$$(2.10) \quad A_{p+2n} \equiv A_p e_{2n} \pmod{p} \quad (2n \leq p + 1).$$

Then (2.9) becomes

$$(2.11) \quad e_{2n+2} \equiv \sum_{r+s \leq n} \frac{(2n)!}{(2r)! (2s)! (2n - 2r - 2s)!} \cdot A_{2r+1} A_{2s+1} e_{2n-2r-2s} \pmod{p}$$

provided $2n < p$.

We now define a set of positive integers e_{2n} by means of $e_0 = 1$,

$$(2.12) \quad e_{2n+2} = \sum_{r+s \leq n} \frac{(2n)!}{(2r)! (2s)! (2n - 2r - 2s)!} A_{2r+1} A_{2s+1} e_{2n-2r-2s} \quad (n = 0, 1, 2, \dots).$$

If we put

$$\phi(x) = \sum_{n=0}^{\infty} e_{2n} \frac{x^{2n}}{(2n)!},$$

then (2.12) is equivalent to

$$(2.13) \quad \phi''(x) = \phi(x)(\phi'(x))^2.$$

Comparing (2.13) with (1.8) we get

$$(2.14) \quad \frac{\phi''(x)}{\phi(x)} = \frac{g''(x)}{g(x)}.$$

It follows that

$$\phi(x)g'(x) - g(x)\phi'(x) = 1.$$

A little manipulation yields

$$\phi(x) = -g(x) \int \frac{dx}{g^2(x)} = -g(x) \int \frac{g'(x) \exp(-\frac{1}{2}g^2(x))dx}{g^2(x)}$$

and we get

$$(2.15) \quad \phi(x) = 1 - \sum_{n=1}^{\infty} \frac{(-1)^n}{2^n n!} \frac{g^{2n}(x)}{2n-1}.$$

Since

$$\frac{(2n)!}{2^n(2n-1)n!} = 1 \cdot 3 \cdot 5 \cdots (2n-3),$$

it follows from (2.2) and (2.15) that

$$(2.16) \quad \phi(x) \equiv 1 - \sum_{n=1}^{m+1} \frac{(-1)^n}{2^n n!} \frac{g^{2n}(x)}{2n-1} \pmod{p},$$

where $p = 2m + 1$.

We notice also that (1.7) gives

$$(2.17) \quad g'(u) \equiv \sum_{n=0}^{\infty} \frac{g^{2n}(x)}{2^n n!} \pmod{p},$$

while (1.8) yields

$$(2.18) \quad g''(u) \equiv \sum_{n=0}^{m-1} \frac{g^{2n+1}(x)}{n!} \pmod{p}.$$

3. We may rewrite (1.8) as

$$(3.1) \quad g''(u) = g(u) \exp g^2(u).$$

Differentiating again and using (1.7) we get

$$(3.2) \quad g'''(u) = (1 + 2g^2(u)) \exp\left(\frac{3}{2}g^2(u)\right).$$

Since

$$\exp\left(\frac{3}{2}g^2(u)\right) \equiv 1 \pmod{3},$$

it is clear that (3.2) implies

$$g'''(u) \equiv 1 + 2g^2(u) \pmod{3}.$$

On the other hand (1.7) gives

$$g'(u) \equiv 1 + \frac{1}{2}g^2(u) \equiv 1 + 2g^2(u) \pmod{3}.$$

We have therefore

$$(3.3) \quad g'''(u) \equiv g'(u) \pmod{3}.$$

Comparison with (1.6) yields

$$(3.4) \quad A_{2n+1} \equiv 1 \pmod{3} \quad (n = 0, 1, 2, \dots).$$

If we differentiate (3.2) two more times we get

$$(3.5) \quad \begin{cases} D^4g(u) = (7g(u) + 6g^3) \exp(2g^2(u)), \\ D^5g(u) = (7 + 46g^2(u) + 24g^4(u)) \exp\left(\frac{5}{2}g^2(u)\right), \end{cases}$$

where $D = d/du$. From the last equation it follows easily that

$$D^5g(u) \equiv 2 + g^2(u) + 4g^4(u) \pmod{5}.$$

Since by (1.7)

$$Dg(u) \equiv 1 + \frac{1}{2}g^2(u) + \frac{1}{8}g^4(u) \equiv 1 + 3g^2(u) + 2g^4(u) \pmod{5},$$

it follows that

$$(3.5) \quad (D^5 - 2D)g(u) \equiv 0 \pmod{5}.$$

This is equivalent to

$$(3.6) \quad A_{2n+5} \equiv 2A_{2n+1} \pmod{5} \quad (n = 0, 1, 2, \dots).$$

Since $A_1 = A_3 = 1$, (2.6) implies

$$(3.7) \quad A_{4n+1} \equiv A_{4n+3} \equiv 2^n \pmod{5} \quad (n = 0, 1, 2, \dots).$$

It is clear from (3.1), (3.2) and (3.5) that

$$(3.8) \quad D^n g(u) = \psi_{n-1}(g(u)) \exp\left(\frac{n}{2}g^2(u)\right),$$

where $\psi_n(z)$ is a polynomial of degree n in z with positive integral coefficients. Differentiating (3.8) we find that $\psi_n(z)$ satisfies the

recurrence

$$(3.9) \quad \psi_n(z) = \psi'_{n-1}(z) + nz\psi_{n-1}(z) .$$

We shall require the residue (mod p) of $\psi_{p-1}(z)$. It is not evident how to obtain this residue using (3.8) and (3.9). We shall therefore use a different method.

The writer has proved [1, §6] that if

$$g(x) = \sum_1^\infty a_n \frac{x^n}{n!} \quad (a_1 = 1)$$

is an H -series without constant term, if

$$\lambda(x) = \sum_1^\infty b_n \frac{x^n}{n!} \quad (b_1 = 1)$$

is the inverse of $g(x)$ and in addition

$$(3.10) \quad b_n \equiv 0 \pmod{p} \quad (n > p) ,$$

where p is an arbitrary prime, then

$$(3.11) \quad a_{n+p} \equiv a_p a_{n+1} \pmod{p} \quad (n \geq 0) .$$

Clearly (3.10) is satisfied in the present case and therefore (3.11) implies

$$(3.12) \quad A_{2n+p} \equiv A_p A_{2n+1} \pmod{p} .$$

Making use of (2.8) we may now state

THEOREM 1. *The coefficients of $g(u)$ defined by (1.6) satisfy*

$$(3.13) \quad A_{2n+p} \equiv -2.4.6 \cdots (p-1)A_{2n+1} \pmod{p} \quad (n = 0, 1, 2, \dots) ,$$

where p is an arbitrary odd prime.

It is easily verified that (3.4) and (3.6) are in agreement with (3.13).

Since (3.12) is equivalent to

$$(D^p - A_p D)g(u) \equiv 0 \pmod{p} ,$$

comparison with (3.8) yields

$$\psi_{p-1}(g(u)) \equiv A_p \exp(\frac{1}{2}g^2(u)) \equiv A_p \sum_{n=0}^m \frac{g^{2n}(u)}{2^{nn}!} \pmod{p} ,$$

where $p = 2m + 1$.

If we put

$$(g(u))^k = \sum_{n=k}^{\infty} A_n^{(k)} \frac{u^n}{n!} \quad (k = 1, 2, 3, \dots),$$

we can show [1, Theorem 10] that $A_n^{(k)}$ satisfies

$$(3.14) \quad A_{n+p}^{(k)} \equiv A_p A_{n+1}^{(k)} \pmod{p} \quad (n \geq 0)$$

for all $k \geq 1$.

We shall apply this result to the series $\phi(u)$ defined by (2.15). Since (3.14) is equivalent to

$$(D^p - A_p D)g^k(u) \equiv 0 \pmod{p},$$

it is clear that (2.16) implies

$$(3.15) \quad (D^p - A_p D)\phi(u) \equiv \frac{(-1)^m}{2^{m+1}(m-1)!} \frac{g^{p+1}(u)}{p} \\ \equiv A_p (D^p - A_p D) \frac{g^{p+1}(u)}{p} \pmod{p},$$

where $p = 2m + 1$.

Now by [1, (6.12)] we have

$$g(u) \equiv \sum_{n=0}^m A_{2n+1} \frac{g_1^{2n+1}(u)}{(2n+1)!} \pmod{p},$$

where

$$(3.16) \quad g_1(u) = u + A_p \frac{g^p(u)}{p!};$$

moreover

$$(3.17) \quad \frac{g_1^p(u)}{p!} \equiv \sum_{n=0}^{\infty} A_p^n \frac{x^{n(p-1)+1}}{(n(p-1)+1)!} \pmod{p}.$$

It follows from (3.16) and (3.17) that

$$(D^p - A_p D) \frac{g^p(u)}{p!} \equiv 1 \pmod{p}.$$

Thus (3.15) becomes

$$(D^p - A_p D)\phi(u) \equiv -A_p g(u) \pmod{p},$$

which is equivalent to

$$(3.18) \quad e_{2n+p+1} \equiv A_p (e_{2n+2} - A_{2n+1}) \pmod{p} \quad (n = 0, 1, 2, \dots).$$

We may state

THEOREM 2. *The coefficients e_{2n} defined by (2.12) satisfy (3.18).*

In view of (2.10) we may rewrite (3.18) as

$$(3.19) \quad A_{2n+p+2} \equiv A_p A_{2n+1} + e_{2n+p+1} \pmod{p} \quad (2n < p).$$

Since

$$A_p A_{2n+1} \equiv A_{2n+p},$$

(3.19) is equivalent to

$$(3.20) \quad A_{2n+p+2} \equiv A_{2n+p} + e_{2n+p+1} \pmod{p} \quad (2n < p).$$

We notice also that repeated application of (3.18) yields

$$(3.21) \quad e_{2n+k}(p-1) \equiv A_p^k e_{2n} - k A_{2n+k}(p-1) - 1 \pmod{p};$$

in particular we have for $k = p$

$$(3.22) \quad e_{2n+p(p-1)} \equiv A_p e_{2n} \pmod{p}.$$

It is also easy to extend (3.20) to

$$(3.23) \quad A_{2n+k(p-1)+1} \equiv k A_{2n+k(p-1)-1} + e_{2n+k(p-1)} \pmod{p} \\ (0 < 2n \leq p+1; k = 1, 2, 3, \dots).$$

Indeed it follows from (3.23) and (3.18) that

$$\begin{aligned} e_{2n+(k+1)(p-1)} &\equiv A_p(e_{2n+k(p-1)} - A_{2n+k(p-1)-1}) \\ &\equiv A_p e_{2n+k(p-1)} - A_{2n+(k+1)(p-1)-1} \\ &\equiv A_p(A_{2n+k(p-1)+1} - k A_{2n+k(p-1)-1}) - A_{2n+(k+1)(p-1)-1} \\ &\equiv A_{2n+(k+1)(p-1)+1} - (k-1)A_{2n+(k+1)(p-1)-1}. \end{aligned}$$

Note that (3.23) does not hold for $k = 0$.

We may state the following theorem which supplements Theorem 2.

THEOREM 3. *The coefficients e_{2n} defined by (2.12) satisfy (3.21), (3.22) and (3.23).*

4. We now derive congruences for $A_{2n+1} \pmod{8}$. From the first of (3.5) we have

$$\begin{aligned} D^4 g(u) &\equiv (-g(u) + 6g^3(u)) \exp(2g^2(u)) \\ &\equiv (-g(u) + 6g^3(u))(1 + 2g^2(u)) \\ &\equiv -g(u) + 4g^3(u) + 4g^5(u) \pmod{8}, \end{aligned}$$

so that

$$(4.1) \quad D^4 g(u) \equiv -g(u) \pmod{8}.$$

This is equivalent to

$$(4.2) \quad A_{2n+5} \equiv -A_{2n+1} \pmod{8} \quad (n = 0, 1, 2, \dots),$$

which implies

$$(4.3) \quad A_{4n+1} \equiv A_{4n+3} \equiv (-1)^n \pmod{8} \quad (n = 0, 1, 2, \dots).$$

This result can however be improved without much difficulty. Working modulo 16 we find that the $\psi_n(z)$ defined by (3.8) and (3.9) satisfy

$$\begin{aligned} \psi_3(z) &\equiv 7z + 6z^3, & \psi_4(z) &\equiv 7 - 2z^2, \\ \psi_5(z) &\equiv -z + 6z^3, & \psi_6(z) &\equiv -1 + 12z^2, \\ \psi_7(z) &\equiv z + 4z^3; \end{aligned}$$

note that the $\psi_n(z)$ are here treated as finite H -series. Then by (3-8)

$$\begin{aligned} D^8g(u) &\equiv (g(u) + 4g^3(u)) \exp(4g^2(u)) \\ &\equiv (g(u) + 4g^3(u))(1 + 4g^2(u)), \end{aligned}$$

so that

$$(4.4) \quad D^8g(u) \equiv g(u) \pmod{16}.$$

This is equivalent to

$$(4.5) \quad A_{2n+9} \equiv A_{2n+1} \pmod{16}.$$

Since $A_1 = A_3 = 1$, $A_5 = 7$, $A_7 \equiv 7 \pmod{16}$, (4.5) implies

$$(4.6) \quad \begin{cases} A_{8n+1} \equiv A_{8n+3} \equiv 1 \pmod{16}, \\ A_{8n+5} \equiv A_{8n+7} \equiv 7 \pmod{16}. \end{cases}$$

We may state

THEOREM 4. *The coefficients A_{2n+1} satisfy (4.2), (4.3), (4.5), (4.6).*

5. We now put

$$(5.1) \quad \frac{u}{g(u)} = \sum_{n=0}^{\infty} \beta_{2n} \frac{u^{2n}}{(2n)!},$$

so that

$$(5.2) \quad \sum_{r=0}^n \binom{2n+1}{2r} A_{2n-2r+1} \beta_{2r} = 0 \quad (n > 0).$$

It follows from (5.2) that the β_{2n} are rational numbers with odd denominators.

From (5.1) and (2.3) we have

$$(5.3) \quad \frac{u}{g(u)} = \sum_{n=0}^{\infty} \frac{c_{2n+1}}{2n+1} \frac{g^{2n}(u)}{(2n)!}.$$

By (2.4)

$$(5.4) \quad c'_{2n+1} = \frac{c_{2n+1}}{2n+1} = (-1)^n \frac{1.3.5 \cdots (2n-1)}{2n+1}.$$

Let p be an odd prime. Then for $2n+1 > p$, c'_{2n+1} is integral (mod p) except possibly when $p|2n+1$. Let

$$2n+1 = kp^r, \quad p+k, \quad r \geq 1.$$

If $k > 1$ it is obvious from (5.4) that c'_{2n+1} is integral (mod p). If $k = 1$, the numerator of c'_{2n+1} is divisible by at least p^w , where $w = (p^{r-1} - 1)/2$. But since

$$\frac{1}{2}(p^{r-1} - 1) \geq r$$

except when $p = 3, r = 2$, it follows that

$$(5.5) \quad p \frac{u}{g(u)} \equiv c_p \frac{g^{p-1}(u)}{(p-1)!} \pmod{p} \quad (p > 3),$$

$$(5.6) \quad 3 \frac{u}{g(u)} \equiv -\frac{g^2(u)}{2!} - \frac{g^8(u)}{8!} \pmod{3}.$$

In the next place we have [1, (6.2)]

$$(5.7) \quad \frac{g^{p-1}(u)}{(p-1)!} \equiv \sum_{n=1}^{\infty} A_p^{n-1} \frac{u^{n(p-1)}}{(n(p-1))!} \pmod{p}$$

for all p . As for $g^8(u)/8!$, we have by (3.16)

$$\frac{g^8(u)}{3!} g_1(u) - u \equiv \sum_1^{\infty} \frac{u^{2n+1}}{(2n+1)!},$$

$$g'_1(u) \equiv 1 + \frac{1}{2}g^2(u)g'(u) \equiv 1 + \frac{1}{2}g^2(u) \equiv g'(u) \pmod{3}.$$

It follows that

$$\frac{g^4(u)}{4!} \equiv \sum_2^{\infty} (n-2) \frac{u^{2n}}{(2n)!} \pmod{3}$$

and a little manipulation leads to

$$(5.8) \quad \frac{g^8(u)}{8!} \equiv \sum_1^{\infty} \frac{u^{6n+2}}{(6n+2)!} \pmod{3}.$$

If we recall that

$$c_p \equiv -A_p \pmod{p}$$

and make use of (5.1), (5.3), (5.5), (5.6), (5.7) and (5.8) we get the following analog of the Staudt-Clausen theorem:

THEOREM 5. *The coefficients β_{2n} defined by (5.1) satisfy*

$$(5.9) \quad \beta_{2n} = G_{2n} - \frac{b}{3} - \sum_{\substack{p-1|2n \\ p>3}} \frac{A_p^{2n/(p-1)}}{p},$$

where G_{2n} is an integer,

$$b = \begin{cases} 2 & n \equiv 1 \pmod{3} \\ 1 & n \not\equiv 1 \pmod{3} \end{cases}$$

and the summation is over all primes $p > 3$ such that $p - 1 \mid 2n$.

6. The following values of A_n were computed by R. Carlitz in the Duke University Computing Laboratory.

$$\begin{aligned} A_5 &= 7, & A_7 &= 127, \\ A_9 &= 17.257, \\ A_{11} &= 7.34807, \\ A_{13} &= 20036983, \\ A_{15} &= 17.134138639, \\ A_{17} &= 7.49020204823, \\ A_{19} &= 127.163.467.6823703, \\ A_{21} &= 23.109.6291767620181, \\ A_{23} &= 7.655889589032992201^*, \\ A_{25} &= 17.94020690191035873697^*, \end{aligned}$$

The numbers marked with an asterisk have not been factored completely but at any rate have no prime divisors $< 10^4$.

REFERENCES

1. L. Carlitz, *Some properties of Hurwitz series*, Duke Math., **16** (1949), 285-295.
2. A. Hurwitz, *Über die Entwicklungs-coeffizienten der lemniscatischen Funktionen*, Mathematische Annalen, **51** (1899), 196-226 (=Mathematische Werke, Basel, 1933, vol. 2, pp. 342-373).
3. J. R. Philip, *The function inverse θ* , Australian J. of Physics, **13** (1960), 13-20.

PACIFIC JOURNAL OF MATHEMATICS

EDITORS

RALPH S. PHILLIPS

Stanford University
Stanford, California

M. G. ARSOVE

University of Washington
Seattle 5, Washington

J. DUGUNDJI

University of Southern California
Los Angeles 7, California

LOWELL J. PAIGE

University of California
Los Angeles 24, California

ASSOCIATE EDITORS

E. F. BECKENBACH

T. M. CHERRY

D. DERRY

M. OHTSUKA

H. L. ROYDEN

E. SPANIER

E. G. STRAUS

F. WOLF

SUPPORTING INSTITUTIONS

UNIVERSITY OF BRITISH COLUMBIA
CALIFORNIA INSTITUTE OF TECHNOLOGY
UNIVERSITY OF CALIFORNIA
MONTANA STATE UNIVERSITY
UNIVERSITY OF NEVADA
NEW MEXICO STATE UNIVERSITY
OREGON STATE UNIVERSITY
UNIVERSITY OF OREGON
OSAKA UNIVERSITY
UNIVERSITY OF SOUTHERN CALIFORNIA

STANFORD UNIVERSITY
UNIVERSITY OF TOKYO
UNIVERSITY OF UTAH
WASHINGTON STATE UNIVERSITY
UNIVERSITY OF WASHINGTON
* * *
AMERICAN MATHEMATICAL SOCIETY
CALIFORNIA RESEARCH CORPORATION
SPACE TECHNOLOGY LABORATORIES
NAVAL ORDNANCE TEST STATION

Mathematical papers intended for publication in the *Pacific Journal of Mathematics* should be typewritten (double spaced), and the author should keep a complete copy. Manuscripts may be sent to any one of the four editors. All other communications to the editors should be addressed to the managing editor, L. J. Paige at the University of California, Los Angeles 24, California.

50 reprints per author of each article are furnished free of charge; additional copies may be obtained at cost in multiples of 50.

The *Pacific Journal of Mathematics* is published quarterly, in March, June, September, and December. Effective with Volume 13 the price per volume (4 numbers) is \$18.00; single issues, \$5.00. Special price for current issues to individual faculty members of supporting institutions and to individual members of the American Mathematical Society: \$8.00 per volume; single issues \$2.50. Back numbers are available.

Subscriptions, orders for back numbers, and changes of address should be sent to Pacific Journal of Mathematics, 103 Highland Boulevard, Berkeley 8, California.

Printed at Kokusai Bunken Insatsusha (International Academic Printing Co., Ltd.), No. 6, 2-chome, Fujimi-cho, Chiyoda-ku, Tokyo, Japan.

PUBLISHED BY PACIFIC JOURNAL OF MATHEMATICS, A NON-PROFIT CORPORATION

The Supporting Institutions listed above contribute to the cost of publication of this Journal, but they are not owners or publishers and have no responsibility for its content or policies.

Rafael Artzy, <i>Solution of loop equations by adjunction</i>	361
Earl Robert Berkson, <i>A characterization of scalar type operators on reflexive Banach spaces</i>	365
Mario Borelli, <i>Divisorial varieties</i>	375
Raj Chandra Bose, <i>Strongly regular graphs, partial geometries and partially balanced designs</i>	389
R. H. Bruck, <i>Finite nets. II. Uniqueness and imbedding</i>	421
L. Carlitz, <i>The inverse of the error function</i>	459
Robert Wayne Carroll, <i>Some degenerate Cauchy problems with operator coefficients</i>	471
Michael P. Drazin and Emilie Virginia Haynsworth, <i>A theorem on matrices of 0's and 1's</i>	487
Lawrence Carl Eggan and Eugene A. Maier, <i>On complex approximation</i>	497
James Michael Gardner Fell, <i>Weak containment and Kronecker products of group representations</i>	503
Paul Chase Fife, <i>Schauder estimates under incomplete Hölder continuity assumptions</i>	511
Shaul Foguel, <i>Powers of a contraction in Hilbert space</i>	551
Neal Eugene Foland, <i>The structure of the orbits and their limit sets in continuous flows</i>	563
Frank John Forelli, Jr., <i>Analytic measures</i>	571
Robert William Gilmer, Jr., <i>On a classical theorem of Noether in ideal theory</i>	579
P. R. Halmos and Jack E. McLaughlin, <i>Partial isometries</i>	585
Albert Emerson Hurd, <i>Maximum modulus algebras and local approximation in C^n</i>	597
James Patrick Jans, <i>Module classes of finite type</i>	603
Betty Kvarda, <i>On densities of sets of lattice points</i>	611
H. Larcher, <i>A geometric characterization for a class of discontinuous groups of linear fractional transformations</i>	617
John W. Moon and Leo Moser, <i>Simple paths on polyhedra</i>	629
T. S. Motzkin and Ernst Gabor Straus, <i>Representation of a point of a set as sum of transforms of boundary points</i>	633
Rajakularaman Ponnuswami Pakshirajan, <i>An analogue of Kolmogorov's three-series theorem for abstract random variables</i>	639
Robert Ralph Phelps, <i>Čebyšev subspaces of finite codimension in $C(X)$</i>	647
James Dolan Reid, <i>On subgroups of an Abelian group maximal disjoint from a given subgroup</i>	657
William T. Reid, <i>Riccati matrix differential equations and non-oscillation criteria for associated linear differential systems</i>	665
Georg Johann Rieger, <i>Some theorems on prime ideals in algebraic number fields</i> ...	687
Gene Fuerst Rose and Joseph Silbert Ullian, <i>Approximations of functions on the integers</i>	693
F. J. Sansone, <i>Combinatorial functions and regressive isols</i>	703
Leo Sario, <i>On locally meromorphic functions with single-valued moduli</i>	709
Takayuki Tamura, <i>Semigroups and their subsemigroup lattices</i>	725
Pui-kei Wong, <i>Existence and asymptotic behavior of proper solutions of a class of second-order nonlinear differential equations</i>	737
Fawzi Mohamad Yaqub, <i>Free extensions of Boolean algebras</i>	761