

On the Funk transform on compact symmetric spaces

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Abstract. We prove that a function on an irreducible compact symmetric space M which is not a sphere is determined by its integrals over the shortest closed geodesics in M . We also prove a support theorem for the Funk transform on rank one symmetric spaces which are not spheres.

1. Introduction

Let M be an irreducible simply connected compact symmetric space and denote by Ξ the space of the shortest closed geodesics γ on M . We associate to a smooth function f on M the function \hat{f} on Ξ defined by setting

$$\hat{f}(\gamma) = \int_{\gamma} f(\gamma(s)) ds,$$

where s is the arc length parameter of γ . Following HELGASON in [8], we call the linear map that sends f to \hat{f} the *Funk transform for M* .

The purpose of this paper is to prove the following two theorems.

Theorem 1.1. *The Funk transform for M is injective if M is not a sphere.*

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Theorem 1.2. *Assume that M has rank one and is not a sphere. Let $\bar{B}_r(p)$ be a closed ball of radius $r > 0$ around a point p in M where r is smaller than the diameter of M . Let f be a function on M such that $\hat{f}(\gamma) = 0$ for every γ in Ξ which does not meet $\bar{B}_r(p)$. Then $f(q) = 0$ for all $q \notin \bar{B}_r(p)$.*

We recall that the simply connected rank one symmetric spaces are precisely the spheres and the projective spaces over the complex numbers, the quaternions and the octonions.

The Funk transform of an odd function on a sphere S^n clearly vanishes. The following result, that we will use in the proof of our theorems, was proved by PAUL FUNK in his doctoral dissertation and published in [1] in 1913.

Theorem 1.3 (Funk [1]). *Let f be a function on a sphere S^n with dimension $n \geq 2$ for which $\hat{f} = 0$. Then f is odd.*

Other proofs of Theorem 1.3 can be found in Appendix A of [3] and in Chapter III, §1B, of [7].

The injectivity of the Funk transform is known for the simply connected projective spaces; see [7], p. 117. There it is based on Helgason's inversion formula for the antipodal Radon transform which is difficult to prove; see Section 4 of Chapter I in [6] (or [9] where a substantially simplified proof based on ideas of Rouvière can be found). If one is only interested in the injectivity of the Funk transform for these spaces, a simple proof can be given; see Remark 3.1.

In [2], GRINBERG proved Theorem 1.1 for the compact groups, the complex and quaternionic Grassmannians, and $SU(n)/SO(n)$.

Theorem 1.2 generalizes Theorem 3.4 in [8].

There is a very interesting explicit inversion formula for the Funk transform of functions with support in sufficiently small balls in compact symmetric spaces; see [8], Corollary 3.3.

2. Helgason spheres

Let $M = G/K$ be an irreducible simply connected compact symmetric space. If the metric of M is given by the negative of the Killing form, then the maximum of the sectional curvature on M is $\|\delta\|^2$, where δ is a highest restricted root. We will normalize the metric on M in such a way that the maximum of the sectional curvature is equal to one. Then the injectivity radius satisfies $i(M) = \pi$.

The following theorem is proved in [4]; see also [5], Chapter VII, §11.

Theorem 2.1. (1) *The shortest closed geodesics in M have length 2π .*

(2) *Let $\gamma_1, \gamma_2 : [0, 1] \rightarrow M$ be two shortest closed geodesics. Then there is an element g in G such that $g \circ \gamma_1 = \gamma_2$.*

(3) *A shortest closed geodesic in M is contained in a totally geodesic sphere of constant curvature one. The maximal dimension of such a sphere is $m(\delta) + 1$, where $m(\delta)$ denotes the multiplicity of a highest restricted root δ . Any two such maximal spheres are conjugate under G .*

The maximal totally geodesic spheres in Theorem 2.1 (3) are called *Helgason spheres*. The projective lines in the simply connected projective spaces are Helgason spheres. They are used to give a simple proof of the injectivity of the Funk transform on projective spaces in Remark 3.1.

It follows immediately from Theorem 2.1 (2) that the space Ξ of shortest closed geodesics in M can be given the structure of a differentiable manifold, since it can be identified with the quotient space G/G_γ , where G_γ is the closed subgroup of G that fixes a given γ in Ξ .

We will need a more precise description of the shortest closed geodesics and the Helgason spheres. Let p be some point in M . We write $M = G/K$ where (G, K) is a symmetric pair and K is the isotropy group of G at p . Consider the corresponding Cartan decomposition $\mathfrak{g} = \mathfrak{k} + \mathfrak{p}$ of the Lie algebra \mathfrak{g} of G . Then the tangent space T_pM can be identified with the subspace \mathfrak{p} in the usual way. Let \mathfrak{a} be a maximal Abelian subspace of \mathfrak{p} . Recall that a linear form α on \mathfrak{a} is a restricted root if $\alpha \neq 0$ and $\mathfrak{g}_\alpha \neq \{0\}$ hold, where the subspace \mathfrak{g}_α is defined by

$$\mathfrak{g}_\alpha = \{X \in \mathfrak{g} \mid (\text{ad } H)^2(X) = -\alpha(H)^2 X \text{ for all } H \in \mathfrak{a}\}.$$

Let \mathcal{R} denote the set of roots. Consider the subspaces $\mathfrak{k}_\alpha = \mathfrak{g}_\alpha \cap \mathfrak{k}$ and $\mathfrak{p}_\alpha = \mathfrak{g}_\alpha \cap \mathfrak{p}$ for $\alpha \in \mathcal{R} \cup \{0\}$. We obtain orthogonal decompositions $\mathfrak{k} = \mathfrak{k}_0 + \sum_{\alpha \in \mathcal{R}^+} \mathfrak{k}_\alpha$ and $\mathfrak{p} = \mathfrak{p}_0 + \sum_{\alpha \in \mathcal{R}^+} \mathfrak{p}_\alpha$ with respect to the Killing form B of \mathfrak{g} , where \mathcal{R}^+ is a set of roots such that $\mathcal{R} = \mathcal{R}^+ \cup (-\mathcal{R}^+)$ is a disjoint decomposition of \mathcal{R} . Notice that $\mathfrak{a} = \mathfrak{p}_0$.

Consider now the exponential map of M denoted by Exp and the lattice $\mathfrak{a}_K = \{X \in \mathfrak{a} \mid \exp(X) \in K\}$ in \mathfrak{a} . It is clear that the flat torus $\text{Exp}(\mathfrak{a})$ can be identified with the coset space $\mathfrak{a}/\mathfrak{a}_K$ in the usual way. Using the Killing form B , we can associate to each restricted root α the vector $H_\alpha \in \mathfrak{a}$ for which $B(H_\alpha, H) = \alpha(H)$ holds for any element H of \mathfrak{a} . Then by Theorem 8.5 in Chapter VII of [5] the lattice \mathfrak{a}_K is generated by the vectors

$$X_\alpha = \frac{2\pi}{B(H_\alpha, H_\alpha)} H_\alpha,$$

$\alpha \in \mathcal{R}$. It follows that the geodesic $\gamma_\alpha : [0, 1] \rightarrow M$ defined by setting $\gamma_\alpha(t) = \text{Exp}(tX_\alpha)$ is closed and it is a shortest closed geodesic if α is a longest root. Note that these vectors X_α , $\alpha \in \mathcal{R}$, form a dual root system of \mathcal{R} in \mathfrak{a} .

The following proposition is proved in [5], Chapter VII, §11.

Proposition 2.2. *Let γ_δ be a closed geodesic corresponding to a longest root δ in \mathcal{R} . Then $\mathfrak{s}_\delta = \mathbb{R}H_\delta + \mathfrak{p}_\delta$ is a Lie triple system and $S = \text{Exp}(\mathfrak{s}_\delta)$ is a Helgason sphere containing γ_δ .*

Let p be some point in M . The *midpoint locus* of p is the set A_p of midpoints of shortest closed geodesics starting in p . It is an immediate consequence of Theorem 2.1 (2) that A_p coincides with the orbit $K(\gamma(1/2))$ where K is the isotropy group of G at p and $\gamma : [0, 1] \rightarrow M$ is some shortest closed geodesic starting at p . The midpoint loci are totally geodesic; see Corollary 11.13 in Chapter VII of [5].

The following proposition is crucial for the proof of Theorem 1.1. Notice that the midpoint locus of a point on a sphere consists only of the antipodal point.

Proposition 2.3. *Let p be some point in M . Then the dimension of the midpoint locus of p is at least two if M is not a sphere.*

PROOF. It is well-known that the proposition is true if M is a compact symmetric space of rank one. We therefore assume that M is an irreducible compact symmetric space of rank greater than one.

Let Y be an element of \mathfrak{a} such that $Y \in \frac{1}{2}\mathfrak{a}_K$ and $Y \notin \mathfrak{a}_K$ hold. This means that $q = \text{Exp}(Y)$ is an antipodal point of p on the closed geodesic $\gamma(t) = \text{Exp}(2tY)$, $t \in [0, 1]$, and $2\alpha(Y) \in \mathbb{Z}\pi$ holds for any $\alpha \in \mathcal{R}$. Then Theorem 11.14 in Chapter VII of [5] implies that the totally geodesic orbit $K(q)$ is isometric to $\text{Exp}(\sum_{\alpha \in \mathcal{R}(Y)} \mathfrak{p}_\alpha)$, where $\mathcal{R}(Y) = \{\alpha \in \mathcal{R}^+ \mid 2\alpha(Y) \in (2\mathbb{Z} + 1)\pi\}$. Moreover, the Lie algebra of the isotropy group K_q of K at the point q coincides with $\mathfrak{k}_q = \mathfrak{k}_0 + \sum_{\alpha \in \mathcal{R}^+ \setminus \mathcal{R}(Y)} \mathfrak{k}_\alpha$.

Select a longest restricted root δ and take the shortest closed geodesic $\gamma_\delta : [0, 1] \rightarrow M$ defined by $\gamma_\delta(t) = \text{Exp}(tX_\delta)$. The irreducibility of M implies that the root system \mathcal{R} is irreducible. Hence, we can find two roots β_1, β_2 in \mathcal{R}^+ such that X_{β_1} and X_{β_2} are not perpendicular to X_δ . Then we obtain that

$$\beta_i(X_\delta) = \pi \cdot \frac{2B(H_{\beta_i}, H_\delta)}{B(H_\delta, H_\delta)} = \pm\pi$$

holds for $i = 1, 2$, where the second equals sign follows from the fact that δ is one of the longest roots and therefore $\|H_\delta\| \geq \|H_{\beta_i}\|$ holds. Therefore $\mathcal{R}(X_\delta/2)$

contains at least two restricted roots and the dimension of the midpoint locus $A_p = K(\text{Exp}(X_\delta/2))$ is at least two. \square

Remark 2.4. We can of course define a midpoint locus with respect to closed geodesics γ_α belonging to roots α which are not longest. In this case, the conclusion of Proposition 2.3 is not necessarily true as the following example shows.

Let us consider a compact symmetric space M whose restricted root system is of type B_2 ; one can for example choose M to be a complex quadric Q^n in $P^{n+1}(\mathbb{C})$ with $n \geq 3$. Select a basis α_1, α_2 of this root system \mathcal{R} , where α_1 is the longer of the two roots. Then the other positive roots are $\beta = \alpha_1 + \alpha_2$ and $\delta = \alpha_1 + 2\alpha_2$. Consider the dual root system in \mathfrak{a} which is represented in Figure 1. This shows that the arc length of the closed geodesic defined by X_β is equal to $2\sqrt{2}\pi$. It follows from the proof above that the orbit $K(\text{Exp}(X_\beta/2))$ of the antipodal point $\text{Exp}(X_\beta/2)$ coincides with a single point.

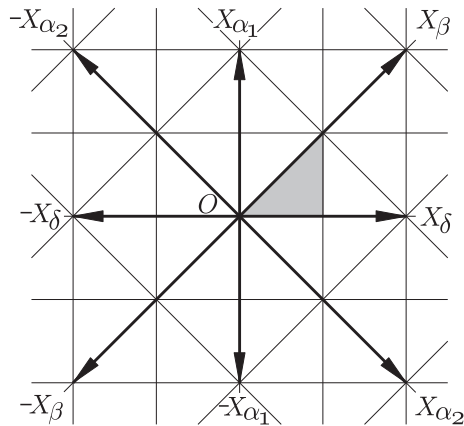


Figure 1. The dual root vectors and the diagram of M in \mathfrak{a} .

3. Proof of Theorem 1.1

Let M be an irreducible simply connected compact symmetric space which is not a sphere. Let f be a smooth function on M such that $\hat{f} = 0$. Assume that f does not vanish. Then f is not constant since otherwise \hat{f} would clearly also be constant and nonvanishing. Now it follows from Sard's Lemma that f has a regular value b in its image. Hence $N = f^{-1}(b)$ is a hypersurface in M .

Let p be some point in N and let S be a Helgason sphere containing p . Let q be the antipodal point of p in S . Since the great circles on S are shortest closed geodesics in Ξ , it follows that $\widehat{f|_S} = 0$. By Funk's Theorem 1.3, $f|_S$ is an odd function. Hence $f(q) = -b$. Now let g be an element of the isotropy group G_p of p and A_q the midpoint locus of q . We would like to prove the inclusion

$$g(A_q) = A_{g(q)} \subset N.$$

First notice that $g(q)$ is the antipodal point of p in $g(S)$ since g fixes p . The value of f being b in p implies that it is equal to $-b$ in $g(q)$. This in turn implies that the value of f on the midpoint locus $A_{g(q)} = g(A_q)$ is equal to b since $A_{g(q)}$ consists of points that are antipodes of $g(q)$ in some Helgason sphere. Hence we have proved that $g(A_q) \subset N$ for every g in G_p as we wanted.

Now let v be a nonzero tangent vector in $T_p A_q$ which exists by Proposition 2.3. If g is in the isotropy group G_p , then $dg_p(v) \in T_p g(A_q) \subset T_p N$ where dg_p denotes the differential map of g at p . Hence the orbit $G_p(v)$ is contained in $T_p N$. Let V be the linear subspace of $T_p N$ spanned by the orbit $G_p(v)$. It is easy to see that V is invariant under G_p . It is clear that V is a proper subspace of $T_p M$ since it is contained in the hyperplane $T_p N$ in $T_p M$. This means that the isotropy representation of G_p is reducible which contradicts the irreducibility of the symmetric space M . This finishes the proof of Theorem 1.1. \square

Remark 3.1. We give a very simple argument that can be used to prove Theorem 1.1 for the already known special case of simply connected projective spaces. Note that the simply connected projective spaces with a symmetric metric are nothing but the simply connected compact rank one spaces excluding the spheres. Let M be such a space. A Helgason sphere in M is nothing but a projective line. Let f be a smooth function on M such that \hat{f} vanishes. Then arguing as in the proof above we see that the restrictions of f to the projective lines are odd functions. Now let p be some point in M . Let P be a projective line through p . Let q be the antipodal point of p on P and let Q be a projective line that meets P perpendicularly in q . Let r be the antipodal point of q in Q and let R be the unique projective line that connects r and p . It is now an easy geometric exercise to show that r and p are antipodal on R . Now we finish the proof as follows. Let a be the value of f in p . The value of f in q is $-a$ since p and q are antipodal in P . The value of f in r is therefore a since q and r are antipodal in Q . Finally the value of f in p is $-a$ since r and p are antipodal in R . We have proved that the value of f in p is both a and $-a$. Hence $a = 0$. This proves that f vanishes identically since p is arbitrary.

4. Proof of Theorem 1.2

In Theorem 1.2, we are dealing with the simply connected symmetric spaces of rank one which are not spheres. These spaces are nothing but the complex and quaternionic projective spaces and the octonion plane. The Helgason spheres in these spaces are precisely the projective lines.

The proof of Theorem 1.2 will be very similar to the one of Theorem 1.1 that we just gave in Section 3. Let q be as in Theorem 1.2. The assumptions in the theorem only give information on q if there is a closed geodesic γ in Ξ passing through q and not meeting $\bar{B}_r(p)$. To be able to carry over the ideas of the proof of Theorem 1.1 we need a Helgason sphere S , which is here a projective line, passing through q and not meeting $\bar{B}_r(p)$.

Proposition 4.1. *Let M be a simply connected compact symmetric space of rank one which is not a sphere. Let $\bar{B}_r(p)$ be a closed ball of radius $r > 0$ around a point p in M where r is smaller than the injectivity radius $i(M)$ of M . Let $q \notin \bar{B}_r(p)$. Then there is a projective line S through q that does not meet the open ball $B_s(p)$ where $s = d(p, q)$. In particular, S does not meet $\bar{B}_r(p)$.*

PROOF. We have normalized the metric on M so that the injectivity radius satisfies $i(M) = \pi$. The diameter $d(M)$ of M then also satisfies $d(M) = \pi$ since M has rank one and is simply connected.

If $s = d(p, q) = \pi$, then q is contained in the cut locus $C(p)$ of p (which for simply connected rank one symmetric spaces coincides with the midpoint locus A_p of p). Note that $C(p)$ is a projective line in M if M is a projective plane and a projective hyperplane in M otherwise. We can now choose a projective line S in $C(p)$ passing through q which then clearly satisfies the claim in the proposition since $d(p, C(p)) = \pi$.

We now assume that $s = d(p, q) < \pi$. Let $\sigma : [0, s] \rightarrow M$ be the shortest geodesic connection between q and p . Let H be the hyperplane in T_qM that is perpendicular to $\dot{\sigma}(0)$. We first show that there is a projective line S passing through q such that $T_qS \subset H$. We continue the geodesic σ beyond p until we reach the first cut point $\hat{p} = \sigma(t_0)$ on σ . Note that $t_0 = \pi$. We let $C(\hat{p})$ denote the cut locus of \hat{p} . Note that $d(\hat{p}, C(\hat{p})) = \pi$. As above we can choose S as a projective line in $C(\hat{p})$ that passes through q . Clearly S and the open ball $B_\pi(\hat{p})$ do not meet.

We will prove that S does not meet the open ball $B_s(p)$. Assume that $\hat{q} \in S \cap B_s(p)$. There is a geodesic τ of length less than s from p to \hat{q} . Then the concatenation $\hat{\tau}$ of $\sigma^{-1}|[s, \pi]$ and τ is a broken geodesic connecting \hat{p} and \hat{q} . The

length of $\hat{\tau}$ is less than π since $L(\sigma|[s, \pi]) = \pi - s$. This is a contradiction since $d(\hat{p}, S) = \pi$. Hence the claim of the proposition follows. \square

The proof of Theorem 1.2 will be very similar to the proof of Theorem 1.1 in Section 3.

PROOF OF THEOREM 1.2. Let q be a point outside of $\bar{B}_r(p)$ and let S a projective line passing through q and not meeting $\bar{B}_r(p)$ which exists by Proposition 4.1. We assume that $f(q) \neq 0$. Set $f(q) = a$. The value of f in the antipode of q on S is $-a$. Hence there is a regular value b in the interval $(-a, a)$ and $N = f^{-1}(b)$ is a hypersurface in M which meets S in a point \hat{q} . Let \tilde{q} be the antipodal point of \hat{q} in S . It follows that $f(\tilde{q}) = -b$. Let $G_{\tilde{q}}$ be the isotropy group at \tilde{q} , and let V be a neighborhood of the identity in $G_{\tilde{q}}$ with the property that $g(S)$ does not meet $\bar{B}_r(p)$ for any g in V . Then $V \cdot \hat{q}$ is a neighborhood of \hat{q} in the midpoint locus $A_{\tilde{q}}$ and it follows that $f|V \cdot \hat{q}$ is constant equal to b , i.e.,

$$V \cdot \hat{q} \subset N.$$

Now let U be a neighborhood of the identity in the isotropy group $G_{\hat{q}}$ such that $g(h(S))$ does not meet $\bar{B}_r(p)$ for any g in U and $h \in V$. Then we can show with methods as in Section 3 that

$$g(V \cdot \hat{q}) \subset N$$

for every $g \in U$.

We choose a nonzero tangent vector v in $T_{\hat{q}}A_{\tilde{q}} = T_{\hat{q}}(V \cdot \hat{q})$ which exists by Proposition 2.3. Arguing as in Section 3, we see that the neighborhood $U \cdot v$ of v in $G_{\hat{q}}(v)$ is contained in $T_{\hat{q}}N$. Hence $G_{\hat{q}}(v)$ is contained in $T_{\hat{q}}N$. This is in contradiction to the irreducibility of M and finishes the proof of Theorem 1.2. \square

5. Conjecture

We conjecture that Theorems 1.1 and 1.2 can be generalized as follows:

Conjecture 5.1. Assume that M is not a sphere. Then there is a number $r_0(M)$ depending on M in the halfopen interval $(0, d(M)]$ with the following property: Let $\bar{B}_r(p)$ be a closed ball of radius $r < r_0(M)$ around a point p . Let f be a function on M such that $\hat{f}(\gamma) = 0$ for every γ in Ξ which does not meet $\bar{B}_r(p)$. Then $f(q) = 0$ for all $q \notin \bar{B}_r(p)$.

Remark 5.2. In Theorem 1.2 we can choose $r_0(M) = d(M)$. In more general symmetric spaces, we expect that $r_0(M)$ has to be chosen smaller than $d(M)$ and maybe also smaller than $i(M)$.

References

- [1] P. FUNK, Über Flächen mit lauter geschlossenen geodätischen Linien, *Math. Ann.* **74** (1913), 278–300.
- [2] E. L. GRINBERG, Integration over minimal spheres in Lie groups and symmetric spaces of compact type, 75 Years of Radon Transform, Vol. 4, Conf. Proc. Lecture Notes Math. Phys., *International Press, Cambridge, MA*, 1994, 167–174.
- [3] V. GUILLEMIN, The Radon transform on Zoll surfaces, *Advances in Math.* **22** (1976), 85–119.
- [4] S. HELGASON, Totally geodesic spheres in compact symmetric spaces, *Math. Ann.* **165** (1966), 309–317.
- [5] S. HELGASON, Differential Geometry, Lie Groups, and Symmetric Spaces, Vol. 80, Pure and Applied Mathematics, *Academic Press, New York – London*, 1978, Reprinted with corrections by the American Mathematical Society 2001.
- [6] S. HELGASON, Groups and Geometric Analysis. Integral geometry, Invariant Differential Operators, and Spherical Functions, Vol. 113, Pure and Applied Mathematics, *Academic Press, Orlando, FL*, 1984, Reprinted with corrections by the American Mathematical Society 2000.
- [7] S. HELGASON, The Radon Transform, Vol. 5, Progress in Mathematics, *Birkhäuser, Boston*, Second Edition 1999.
- [8] S. HELGASON, The inversion of the X-ray transform on a compact symmetric space, *J. Lie Theory* **17** (2007), 307–315.
- [9] S. HELGASON, Integral Geometry and Radon Transforms, Monograph to appear.

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