COMPACT HOMOGENEOUS LCK MANIFOLDS ARE VAISMAN

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Abstract. We prove that any compact homogeneous locally conformally Kähler manifold has parallel Lee form.

Theorem 1 below has been claimed by K. Hasegawa and Y. Kamishima in [1] *and* [2] *and a partial result also appeared in* [3]. *At the time of writing, it is not clear to us that the arguments presented in* [1] *and* [2] *are complete. We here present a complete simple proof of this result.*

A Hermitian manifold (M, g, J) is called *locally conformally Kähler* — lcK for short — if, in some neighbourhood of any point of M, the Hermitian structure can be made Kähler by some conformal change of the metric. Equivalently, (M, g, J) is lcK if there exists a *closed* real 1-form θ, called the *Lee form* of the Hermitian structure, such that the *Kähler form* $\omega := g(J\cdot, \cdot)$ satisfies:

$$d\omega = \theta \wedge \omega. \tag{1}$$

A lcK Hermitian structure is called *strictly* lcK if the Lee form θ is not identically zero, and *Vaisman* if θ is a non-zero parallel 1-form with respect to the Levi-Civita connection of the metric g. Equivalently, since θ is closed, a strictly lcK manifold is Vaisman if the *Lee vector field* $\xi = \theta^\sharp$ is Killing, i.e. $\mathcal{L}_\xi g = 0$, where $\mathcal{L}_X$ denote the Lie derivative along a vector field X. In general, the Lee vector field ξ and the vector field $J\xi$ (sometimes called the *Reeb vector field* of the lcK structure) are neither Killing, nor holomorphic (meaning that $\mathcal{L}_\xi J = 0$), but we always have $\mathcal{L}_{J\xi}\omega = 0$, since $\mathcal{L}_{J\xi}\omega = -d\theta + \theta(J\xi)\,\omega + \theta \wedge \theta = 0$.

By a *compact homogeneous lcK manifold* we mean a compact, connected, strictly lcK manifold (M, g, J, ω), equipped with a transitive and effective left-action of a (compact, connected) Lie group G, which preserves the whole Hermitian structure, i.e. the Riemannian metric g, the (integrable) complex structure J and the 2-form ω. We then have:

Theorem 1. *Any compact homogeneous lcK manifold (M, g, J, ω) is Vaisman.*

Date: September 17, 2014.
This work was supported by the LEA Math-Mode.

Before starting the proof of Theorem 1, we recall a number of general, well-known facts, concerning a compact homogeneous manifold (M, g), equipped with a left-action, effective and transitive, of a (connected) compact Lie group G. Without loss of generality, we assume that the stabilizer G_x of any point x of M in G is connected. We denote by $\mathfrak{g}$ the Lie algebra of G and we fix an Ad_G-invariant positive definite inner product, B, on $\mathfrak{g}$. The induced (infinitesimal) action of $\mathfrak{g}$ is an injective linear map $\sigma : \mathsf{a} \mapsto \hat{\mathsf{a}}$ from $\mathfrak{g}$ to the space, $\mathrm{Vect}(M)$, of (smooth) vector fields on M, defined by:

$$\hat{\mathsf{a}}(x) = \frac{d}{dt}\Big|_{t=0} \exp(t\,\mathsf{a}) \cdot x, \tag{2}$$

for any a in $\mathfrak{g}$ and any x in M, where $\exp : \mathfrak{g} \to G$ denotes the exponential map and $\cdot$ the action of G on M. Since the G-action on M is a left-action, σ is an *anti-isomorphism* from $\mathfrak{g}$ to $\hat{\mathfrak{g}}$, equipped with the usual bracket of vector fields: $[\hat{\mathsf{a}}, \hat{\mathsf{b}}] = -\widehat{[\mathsf{a}, \mathsf{b}]}$.

We denote by Inv the space of G-invariant vector fields on M, which is a Lie subalgebra of $\mathrm{Vect}(M)$. Any element Z of Inv commutes with all elements of $\hat{\mathfrak{g}}$. In particular

$$\mathsf{Inv} \cap \hat{\mathfrak{g}} = \hat{\mathfrak{c}}, \tag{3}$$

where $\hat{\mathfrak{c}}$ denotes the image in $\hat{\mathfrak{g}}$ of the center, $\mathfrak{c}$, of $\mathfrak{g}$.

For any x in M, we denote by σ_x the map $\mathsf{a} \mapsto \hat{\mathsf{a}}(x)$, from $\mathfrak{g}$ to the tangent space T_xM of M at x, and by σ_x^* its metric adjoint, from (T_xM, g_x) to $(\mathfrak{g}, B)$, so that:

$$B(\sigma_x^*(X), \mathsf{a}) = g_x(X, \sigma_x(\mathsf{a})), \tag{4}$$

for any X in T_xM and any a in $\mathfrak{g}$. The kernel, $\mathfrak{g}_x$, of σ_x, is a Lie subalgebra of $\mathfrak{g}$, namely the Lie algebra of the stabilizer, G_x, of x in G, whereas the image of σ_x^* in $\mathfrak{g}$ is the B-orthogonal complement, $\mathfrak{g}_x^\perp$, of $\mathfrak{g}_x$. The Lie algebra $\mathfrak{g}_x$ acts on T_xM by $\mathsf{a} \cdot X = [\tilde{X}, \hat{\mathsf{a}}](x) = (D^g_X \hat{\mathsf{a}})\,(x)$ for any a in $\mathfrak{g}_x$ and any X in T_xM, where $\tilde{X}$ here stands for any local vector field around x such that $\tilde{X}(x) = X$ and D^g denotes the Levi-Civita connection of g. We then have

$$\sigma_x[\mathsf{a}, \mathsf{b}] = \mathsf{a} \cdot \sigma_x(\mathsf{b}), \qquad \sigma_x^*(\mathsf{a} \cdot X) = [\mathsf{a}, \sigma_x^*(X)], \tag{5}$$

for any a in $\mathfrak{g}_x$, any b in $\mathfrak{g}$ and any X in T_xM.

For any chosen point x in M, the evaluation map $\mathsf{ev}_x : Z \mapsto \mathsf{ev}_x(Z) := Z(x)$, from Inv to T_xM, is injective, and $Z(x)$ belongs to the space, denoted by $(T_xM)^{\mathfrak{g}_x}$, of those X in T_xM such that $\mathsf{a} \cdot X = 0$ for any a in $\mathfrak{g}_x$; conversely, any X in $(T_xM)^{\mathfrak{g}_x}$ is equal to $Z(x)$ for a unique Z in Inv. Then, ev_x is a linear *isomorphism* from Inv to $(T_xM)^{\mathfrak{g}_x}$, whose inverse is denoted by ev_x^{-1}. On the other hand, for any X in $(T_xM)^{\mathfrak{g}_x}$, we have $X = \hat{\mathsf{b}}(x)$ for some b in $\mathfrak{g}$, which is uniquely defined up to the addition of an element of $\mathfrak{g}_x$ and is such that $[\mathsf{a}, \mathsf{b}]$ belongs to $\mathfrak{g}_x$

for any a in $\mathfrak{g}_x$, meaning that b belongs to the normalizer, $\mathrm{N}_{\mathfrak{g}}(\mathfrak{g}_x)$, of $\mathfrak{g}_x$ in $\mathfrak{g}$; conversely, for any b in $N_{\mathfrak{g}}(\mathfrak{g}_x)$, $\hat{\mathsf{b}}(x)$ is the value at x of a (unique) element of Inv. For any chosen x in M, we thus get a linear isomorphism

$$\mathsf{Inv} = \mathrm{N}_{\mathfrak{g}}(\mathfrak{g}_x)/\mathfrak{g}_x, \tag{6}$$

according to which $\mathsf{b} \mod \mathfrak{g}_x$ is identified with $\mathsf{ev}_x^{-1}(\sigma_x(\mathsf{b}))$, for any b in $\mathrm{N}_{\mathfrak{g}}(\mathfrak{g}_x)$. This isomorphism is actually a Lie algebra isomorphism.

In general, the rank, $\mathsf{rk}\,\mathfrak{l}$, of a Lie algebra $\mathfrak{l}$ of compact type (= the Lie algebra of a compact Lie group) can be defined as the dimension of a maximal abelian Lie subalgebra. In particular, $\mathsf{rk}\,\mathrm{N}_{\mathfrak{g}}(\mathfrak{g}_x) \leq \mathsf{rk}\,\mathfrak{g}$ and it then follows from (6) that

$$\mathsf{rk}\,\mathsf{Inv} \leq \mathsf{rk}\,\mathfrak{g} - \mathsf{rk}\,\mathfrak{g}_x. \tag{7}$$

Proof of Theorem 1. We now assume that the homogeneous Riemannian manifold (M, g) is equipped with a compatible G-invariant lcK Hermitian structure as explained above. In particular, Inv is J-invariant, since J is G-invariant, and contains the Lee vector field ξ and $J\xi$ (notice however that Inv is *not* a priori a complex Lie algebra, as J is not preserved in general by the elements of Inv). Since the G-action on M preserves the Kähler form ω, it preserves $d\omega$ as well, hence also the Lee form θ. Since, moreover, $d\theta = 0$, it follows that $\theta(\hat{\mathsf{a}})$ is *constant* and that $\theta([\hat{\mathsf{a}}, \hat{\mathsf{b}}]) = 0$, for any $\hat{\mathsf{a}}, \hat{\mathsf{b}}$ in $\hat{\mathfrak{g}}$. Alternatively, θ determines an element, $\tilde{\theta}$, of $\mathfrak{g}^*$, defined by $\tilde{\theta}(\mathsf{a}) := \theta(\hat{\mathsf{a}})$, which vanishes on the derived Lie subalgebra $[\mathfrak{g}, \mathfrak{g}]$. Being of compact type, $\mathfrak{g}$ splits as $\mathfrak{g} = \mathfrak{c} \oplus \mathfrak{s}$, where $\mathfrak{s} = [\mathfrak{g}, \mathfrak{g}]$ is the semi-simple part of $\mathfrak{g}$. We infer the existence of t in $\mathfrak{c}$ such that $\tilde{\theta}(\mathsf{t}) = 1$, whose image in $\hat{\mathfrak{c}} = \mathsf{Inv} \cap \hat{\mathfrak{g}}$ will be denoted by T, instead of $\hat{\mathsf{t}}$; we then have $\theta(T) = 1$. Since θ is closed, the kernel, $\mathfrak{g}_0$, of $\tilde{\theta}$ in $\mathfrak{g}$ is a Lie subalgebra of $\mathfrak{g}$ and we get the following B-orthogonal decomposition

$$\mathfrak{g} = \langle \mathsf{t} \rangle \oplus \mathfrak{g}_0, \tag{8}$$

where $\langle \mathsf{t} \rangle$ denotes the 1-dimensional subspace of $\mathfrak{g}$ generated by t. The 1-form ψ defined by

$$\psi := -\iota_T \omega, \tag{9}$$

is G-invariant, in particular $\mathcal{L}_T \psi = 0$, from which we infer, by using (1): $d\psi = \iota_T d\omega = \theta(T)\,\omega + \theta \wedge \psi$, hence

$$\omega = d\psi - \theta \wedge \psi. \tag{10}$$

Notice that (10) implies that $\theta \wedge \psi \neq 0$ at each point of M, since ω is everywhere non-degenerate, whereas $\iota_T d\psi = 0$; it follows that the G-invariant vector fields $T, J\xi$ are independent at each point of M. Since

$[T, J\xi] = \mathcal{L}_T(J\xi) = 0$, T and $J\xi$ generate a 2-dimensional abelian Lie subalgebra of Inv, so that

$$\mathsf{rk}\,\mathsf{Inv} \geq 2. \tag{11}$$

From (10), we readily infer that $\mathfrak{c}$ is either 1-dimensional, generated by T, or 2-dimensional, generated by T and by $J\xi$, which is then an element of $\hat{\mathfrak{c}} = \mathsf{Inv} \cap \hat{\mathfrak{g}}$. Indeed, suppose that $\mathfrak{c}$ is of dimension greater than 1. There then exists $\mathsf{v} \neq 0$ in $\mathfrak{c}$ such that $\tilde{\theta}(\mathsf{v}) = 0$. Again, we denote by V its image in $\hat{\mathfrak{c}} = \mathsf{Inv} \cap \hat{\mathfrak{g}}$, instead of $\hat{\mathsf{v}}$. Since ψ is G-invariant, we have $\mathcal{L}_V \psi = 0$, so that, by (10), $\iota_V \omega = \psi(V)\,\theta$. This implies that V is then equal to a (non-zero) multiple of $J\xi$.

Choose any x in M and denote by w_x the element of $\mathfrak{g}$ defined by

$$\mathsf{w}_x = \sigma_x^*\big((JT)(x)\big), \tag{12}$$

so that $B(\mathsf{w}_x, \mathsf{a}) = g_x(JT, \sigma_x(\mathsf{a})) = -\psi(\sigma_x(\mathsf{a})) = -\psi(\hat{\mathsf{a}}(x))$, for any a in $\mathfrak{g}$, where ψ is the G-invariant 1-form defined by (9). In particular, w_x sits in $\mathfrak{g}_0$, since $\psi(T) = 0$, and is B-orthogonal to $\mathfrak{g}_x$. Denote by $C_{\mathfrak{g}_0}(\mathsf{w}_x)$ the commutator of w_x in $\mathfrak{g}_0$ and pick any a in $\mathfrak{g}_0$. Then, a belongs to $C_{\mathfrak{g}_0}(\mathsf{w}_x)$ if and only if $B([\mathsf{w}_x, \mathsf{a}], \mathsf{b}) = 0$ for any b in $\mathfrak{g}_0$. Since $B([\mathsf{w}_x, \mathsf{a}], \mathsf{b}) = B(\mathsf{w}_x, [\mathsf{a}, \mathsf{b}]) = \psi([\hat{\mathsf{a}}, \hat{\mathsf{b}}](x)) = d\psi(\hat{\mathsf{a}}(x), \hat{\mathsf{b}}(x))$, this occurs if and only if $\iota_{\hat{\mathsf{a}}(x)} d\psi = 0$, if and only if $\iota_{\hat{\mathsf{a}}(x)}\omega - \psi(\hat{\mathsf{a}}(x))\,\theta(x) = 0$ (by using (10) and $\theta(\hat{\mathsf{a}}) = 0$). We eventually get that a belongs to $C_{\mathfrak{g}_0}(\mathsf{w}_x)$ if and only if $\hat{\mathsf{a}}(x) = -\psi(\hat{\mathsf{a}}(x))\,(J\xi)(x) = B(\mathsf{w}_x, \mathsf{a})\,(J\xi)(x)$. We infer that $\sigma_x(\mathsf{w}_x) = B(\mathsf{w}_x, \mathsf{w}_x)\,J\xi(x)$ and that

$$C_{\mathfrak{g}_0}(\mathsf{w}_x) = \langle \mathsf{w}_x \rangle \oplus \mathfrak{g}_x, \tag{13}$$

where the sum is B-orthogonal. Since w_x is contained in a maximal abelian Lie subalgebra of $\mathfrak{g}_0$, which is contained in $C_{\mathfrak{g}_0}(\mathsf{w}_x)$, we have: $\mathsf{rk}\, C_{\mathfrak{g}_0}(\mathsf{w}_x) = \mathsf{rk}\,\mathfrak{g}_0 = \mathsf{rk}\,\mathfrak{g} - 1$. It then follows from (13) that

$$\mathsf{rk}\,\mathfrak{g}_x = \mathsf{rk}\,\mathfrak{g} - 2. \tag{14}$$

By using (7), we infer $\mathsf{rk}\,\mathsf{Inv} \leq 2$, hence, by (11):

$$\mathsf{rk}\,\mathsf{Inv} = 2. \tag{15}$$

Being a Lie algebra of compact type of rank 2, with non-trivial center (since it contains T), Inv is isomorphic either to the abelian Lie algebra $\mathbb{R} \oplus \mathbb{R}$ or to the unitary Lie algebra $\mathfrak{u}_2 = \mathbb{R} \oplus \mathfrak{su}_2$. Notice that the latter case can only occur if $\mathfrak{c} = \langle \mathsf{t} \rangle$, since $\hat{\mathfrak{c}} \cong \mathfrak{c}$ is contained in Inv, whereas the center of $\mathfrak{u}_2$ is of dimension 1.

Case 1. If $\mathsf{Inv} \cong \mathbb{R} \oplus \mathbb{R}$, it is generated by T and $J\xi$, which, as already observed, are independent at each point of M. Since JT belongs to Inv, we thus have

$$JT = a\,T + b\,J\xi, \tag{16}$$

for some real numbers a, b, with $b \neq 0$. Now, T preserves ω and J, as do any vector field in $\hat{\mathfrak{g}}$, so JT preserves J, since J is integrable. It follows that $J\xi = \frac{1}{b}(JT - a\,T)$ preserves J as well. We already observed that $J\xi$ preserves ω for *any* lcK structure: $J\xi$ is then a Killing vector field with respect to g. It then follows from (16) that JT is a Killing vector field. Finally, $\xi = \frac{1}{b}(T + a\,JT)$ is also a Killing vector field, meaning that the lcK structure is Vaisman.

Case 2. It remains to deal with the case when $\mathfrak{c} = \langle \mathsf{t} \rangle$ is 1-dimensional and $\mathsf{Inv} \cong \mathfrak{u}_2 = \mathbb{R} \oplus \mathfrak{su}_2$. For convenience, we normalize B so that $B(\mathsf{t}, \mathsf{t}) = 1$ and $B(\mathsf{w}_x, \mathsf{w}_x) = 1$, where w_x has been defined by (12), so that $\sigma_x(\mathsf{w}_x) = (J\xi)(x)$ (where x is any chosen point in M). Denote by e_0 a generator of the center $\mathbb{R}$ of $\mathfrak{u}_2$, and by e_1, e_2, e_3 a triple of generators of $\mathfrak{su}_2$, such that $[e_2, e_3] = e_1$, $[e_2, e_3] = e_1$, $[e_3, e_1] = e_2$. Via (6), we may identify e_0 with $\mathsf{t} \mod \mathfrak{g}_x$ and e_1, say, with $\mathsf{w}_x \mod \mathfrak{g}_x$, in order that the restriction of ω — given by (10) — to $\mathrm{N}_{\mathfrak{g}}(\mathfrak{g}_x)/\mathfrak{g}_x$ coincide with the standard form $\omega_0 = e_0 \wedge e_1 + e_2 \wedge e_3$; we here identify e_0, e_1, e_2, e_3 with their B-duals in $\mathfrak{g}^*$, so that $\theta = e_0$, $\psi(x) = -e_1$ and $(d\psi)(x) = e_2 \wedge e_3$ (by identifying θ with $\tilde{\theta}$ and, similarly, $\psi(x)$ with $\mathsf{a} \mapsto \psi(\hat{\mathsf{a}}(x))$ in $(\mathfrak{g}/\mathfrak{g}_x)^*$). It remains to determine the complex structure J of Inv in terms of the generators e_0, e_1, e_2, e_3. Without loss of generality, the generators X, Y of the corresponding 2-dimensional complex space $\Theta_J^{(0,1)}$ of elements of type $(0,1)$ in $\mathsf{Inv} \otimes \mathbb{C} = \mathbb{C}\,e_0 \oplus \mathbb{C}\,e_1 \oplus \mathbb{C}\,e_2 \oplus \mathbb{C}\,e_3$ can be chosen of the form $X = e_0 + \sum_{i=1}^3 a_i\,e_i$, $\quad Y = \sum_{i=1}^3 b_i\,e_i$, where a_i, b_i are complex numbers, which must satisfy the following three conditions:

(i) $\Theta_J^{(0,1)}$ is ω-*Lagrangian*, i.e. $\omega(X, Y) = 0$, where ω is extended to a $\mathbb{C}$-bilinear form on $(\mathbb{R} \oplus \mathfrak{su}_2) \otimes \mathbb{C}$;

(ii) $\Theta_J^{(0,1)}$ is *involutive*, meaning that $[X, Y] = \lambda\,X + \mu\,Y$, for some complex numbers λ, μ;

(iii) $g := \omega_0(\cdot, J\cdot)$ must be positive definite on $\mathbb{R} \oplus \mathfrak{su}_2$, meaning that $i\,\omega(Z, \bar{Z}) > 0$, for any Z in $\Theta_J^{(0,1)}$.

It is easily checked that the first condition (i) is expressed by

$$b_1 + a_2\,b_3 - a_3\,b_2 = 0, \tag{17}$$

whereas the integrability condition (ii) implies $\lambda = 0$ and is then equivalent to the system

$$\begin{aligned} -\mu\,b_1 - a_3\,b_2 + a_2\,b_3 &= 0, \\ a_3\,b_1 - \mu\,b_2 - a_1\,b_3 &= 0, \\ a_1\,b_2 - a_2\,b_1 - \mu\,b_3 &= 0. \end{aligned} \tag{18}$$

If $b_1 \neq 0$, we infer from (17) that $\mu = -1$, so that, the system (18) has a non-trivial solution in b_1, b_2, b_3 if and only if a_1, a_2, a_3 are related by $\sum_{i=1}^3 a_i^2 + 1 = 0$, the solution then being $b_1 = a_1\,a_3 - a_2$, $b_2 = a_2\,a_3 + a_1$, $b_3 = a_3^2 + 1$. We thus get $Y = a_3 \sum_{i=1}^3 a_i\,e_i - a_2\,e_1 + a_1\,e_2 + e_3 =$

$-a_3\, e_0 - a_2\, e_1 + a_1\, e_2 + e_3 \mod X$. It follows that $\Theta_J^{(0,1)}$ meets the first two conditions (i) and (ii), with $b_1 \neq 0$, if and only it is generated by X, Y of the form $X = e_0 + \sum_{i=1}^3 a_i\, e_i$, $\quad Y = -a_3\, e_0 - a_2\, e_1 + a_1\, e_2 + e_3$, with $\sum_{i=1}^3 a_i^2 + 1 = 0$. As for the positivity condition (iii), we easily compute $\omega_0(X, \bar{X}) = \bar{a}_1 - a_1 + a_2\, \bar{a}_3 - \bar{a}_2\, a_3 = -\omega_0(Y, \bar{Y})$, which shows that (iii) is actually *never* satisfied if $b_1 \neq 0$. We thus have $b_1 = 0$, which, by (17), implies $a_2 b_3 - a_3 b_2 = 0$, so that $Y = b_2\, e_2 + b_3\, e_3$, whereas $X = e_0 + a_1\, e_1 \mod Y$; by changing the notation, $\Theta_J^{(0,1)}$ is then generated by $X := e_0 + a_1\, e_1$ and $Y := b_2\, e_2 + b_3\, e_3$. Moreover, since $[X, Y] = a_1\,(-b_3\, e_2 + b_2\, e_3)$, the integrability condition (ii) is satisfied if and only if $b_2 = k\, b_3$ and $b_3 = -k\, b_2$, for some complex number k, which must be equal to $\pm i$. If $k = i$, we have $Y = e_2 - i\, e_3$, hence $i\, \omega_0(Y, \bar{Y}) = -2$, which is negative. We thus have $k = -i$, hence $Y = e_2 + i\, e_3$, whereas $i\, \omega_0(X, \bar{X}) = 2\, \mathfrak{Im}(a)$, by setting $a_1 = a$, so that $\mathfrak{Im}(a) > 0$. The only suitable complex structures J on $\mathbb{R} \oplus \mathfrak{su}_2$ are therefore of the form

$$\begin{aligned} Je_0 &= \frac{\mathfrak{Re}(a)}{\mathfrak{Im}(a)}\, e_0 + \frac{|a|^2}{\mathfrak{Im}(a)}\, e_1, \quad Je_1 = -\frac{1}{\mathfrak{Im}(a)}\, e_0 - \frac{\mathfrak{Re}(a)}{\mathfrak{Im}(a)}\, e_1, \\ Je_2 &= e_3, \qquad Je_3 = -e_2, \end{aligned} \tag{19}$$

with $\mathfrak{Im}(a) > 0$. Since $e_0 = \mathsf{t} \mod \mathfrak{g}_x$ and $e_1 = \mathsf{w}_x \mod \mathfrak{g}_x$ represent T and $J\xi$ respectively in Inv, via (6), it follows that (16) is again satisfied in Inv, with $b = \frac{|a|^2}{\mathfrak{Im}(a)} > 0$; we then conclude as before that ξ is Killing, i.e. that the lcK structure is Vaisman. $\square$

References

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