Singularities of timelike Anti de Sitter Gauss images

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Abstract We study the differential geometry of spacelike surfaces in Anti de Sitter 3-space from the viewpoint of Legendrian singularity theory. We define the timelike Anti de Sitter Gauss image on spacelike surface and investigate the geometric meanings of singularities.

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1 Introduction

Recently, there appeared several articles of differential geometry on submanifolds in Lorentzian space forms as applications of singularity theory [5, 7, 8, 9, 10, 11, 12, 13, 14]. Minkowski space is a flat Lorentzian space form and de Sitter space is the Lorentzian space form with positive constant curvature. The Lorentzian space form with the negative constant curvature is called Anti de Sitter space which is a vacuum solution of the Einstein equation. However, there are very few researches on differential geometry of submanifolds in Anti de Sitter space as applications of singularity theory so far as we know. In this paper we study the differential geometry on spacelike surfaces in Anti de Sitter 3-space from the viewpoint of the theory of Legendrian singularities.

On the other hand, hypersurfaces in hyperbolic space have been studied in [6]. The basic notions and tools for the study of the differential geometry of hypersurfaces in hyperbolic space have been established. Especially, the hyperbolic Gauss indicatrix of a hypersurface in hyperbolic space has been explicitly described and the contact of hypersurfaces with model hypersurfaces has been systematically studied as an application of singularity theory to the hyperbolic Gauss indicatrix. Our aim in this paper is to develop the analogous study for spacelike surfaces in Anti de Sitter 3-space. In §2 we first show the basic notions on semi-Euclidean 4-space with index 2 and contact geometry. Especially we have proved the Legendrian duality theorem (Theorem 2.1) between Anti de Sitter 3-spaces, which is the key to see the view of the whole. In §3 we develop the local differential geometry of spacelike surfaces in Anti de Sitter 3-space and introduce the notion of timelike Anti de Sitter Gauss image of a spacelike surface in Anti de Sitter 3-space. Corresponding to this notion we define the Anti de

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Sitter Gauss Kronecker (briefly, AdS-G-K) curvature and consider the geometry meaning of this curvature. One of our conclusions asserts that the AdS-G-K curvature describes the contact of spacelike surfaces with some model surfaces (i.e., AdS-great hyperboloids). We introduce the notion of timelike height function in §4, named AdS-height function, which is useful to show that the TAdS-Gauss image has a singular point if and only if the AdS-G-K curvature vanished at such point. In §5, 6, we apply mainly the theory of Legendrian singularities for the study of TAdS-Gauss image and interpret the TAdS-Gauss image as a Legendrian map in a nature Legendrian fibration whose generating family is the AdS-height function on spacelike surface. We also study the contact of spacelike surfaces with AdS-great hyperboloids. In §7 we study generic properties. In §8, we give a classification of singularities of TAdS-Gauss image. In the last part, §9 we introduce the notion of the AdS-Monge form of a spacelike surface in Anti de Sitter 3-space and give some examples.

We shall assume throughout the whole paper that all the maps and manifolds are $C^\infty$ unless the contrary is explicitly stated.

2 The basic notations and the duality theorem

In this section we prepare basic notions on semi-Euclidean 4-space with index 2 and contact geometry.

Let $\mathbb{R}^4 = \{ (x_1, \ldots, x_4) | x_i \in \mathbb{R} \ (i = 1, \ldots, 4) \}$ be a 4-dimensional vector space. For any vectors $\mathbf{x} = (x_1, \ldots, x_4)$ and $\mathbf{y} = (y_1, \ldots, y_4)$ in $\mathbb{R}^4$, the pseudo scalar product of $\mathbf{x}$ and $\mathbf{y}$ is defined to be $\langle \mathbf{x}, \mathbf{y} \rangle = -x_1y_1 - x_2y_2 + x_3y_3 + x_4y_4$. We call $(\mathbb{R}^4, \langle \cdot, \cdot \rangle)$ a semi-Euclidean 4-space with index 2 and write $\mathbb{R}^4_2$ instead of $(\mathbb{R}^4, \langle \cdot, \cdot \rangle)$.

We say that a non-zero vector $\mathbf{x}$ in $\mathbb{R}^4_2$ is spacelike, null or timelike if $\langle \mathbf{x}, \mathbf{x} \rangle > 0, \langle \mathbf{x}, \mathbf{x} \rangle = 0$ or $\langle \mathbf{x}, \mathbf{x} \rangle < 0$ respectively. The norm of the vector $\mathbf{x} \in \mathbb{R}^4_2$ is defined by $\| \mathbf{x} \| = \sqrt{|\langle \mathbf{x}, \mathbf{x} \rangle |}$. For a vector $\mathbf{n} \in \mathbb{R}^4_2$ and a real number $c$, we define the hyperplane with pseudo-normal $\mathbf{n}$ by

$$\mathcal{H}(\mathbf{n}, c) = \{ \mathbf{x} \in \mathbb{R}^4_2 | \langle \mathbf{x}, \mathbf{n} \rangle = c \}.$$ 

We call $\mathcal{H}(\mathbf{n}, c)$ a Lorentz hyperplane, a semi-Euclidean hyperplane of index 2 or a null hyperplane if $\mathbf{n}$ is timelike, spacelike or null respectively.

We now define Anti de Sitter 3-space (briefly, AdS 3-space) by

$$H^3_1 = \{ \mathbf{x} \in \mathbb{R}^4_2 \ | \ \langle \mathbf{x}, \mathbf{x} \rangle = -1 \}$$

For any $\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3 \in \mathbb{R}^4_2$. We define a vector $\mathbf{X}_1 \wedge \mathbf{X}_2 \wedge \mathbf{X}_3$ by

$$\mathbf{X}_1 \wedge \mathbf{X}_2 \wedge \mathbf{X}_3 = \begin{vmatrix} -e_1 & -e_2 & e_3 & e_4 \\ x_1 & x_2 & x_3 & x_4 \\ x_2 & x_3 & x_4 & x_1 \\ x_3 & x_4 & x_1 & x_2 \\ x_4 & x_1 & x_2 & x_3 \end{vmatrix},$$

where $e_1, e_2, e_3, e_4$ is the canonical basis of $\mathbb{R}^4_2$ and $\mathbf{X}_i = (x^i_1, x^i_2, x^i_3, x^i_4)$. We can easily check that

$$\langle \mathbf{X}, \mathbf{X}_1 \wedge \mathbf{X}_2 \wedge \mathbf{X}_3 \rangle = \det(\mathbf{X}, \mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3),$$

so that $\mathbf{X}_1 \wedge \mathbf{X}_2 \wedge \mathbf{X}_3$ is pseudo-orthogonal to any $\mathbf{X}_i$ (for $i = 1, 2, 3$).

In this paper We stick to spacelike surfaces in Anti de Sitter 3-space $H^3_1$. Typical spacelike surfaces in $H^3_1$ are given by the intersection of $H^3_1$ with a Lorentz hyperplane in $\mathbb{R}^4_2$:

$$\mathcal{A}(\mathbf{n}, c) = H^3_1 \cap \mathcal{H}(\mathbf{n}, c),$$

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where $\|n\| > |c|$. We say that $AH(n, c)$ is a *AdS-hyperboloid* in the Anti de Sitter 3-space. In particular, we call $AH(n, 0)$ the *AdS-great-hyperboloid*.

On the other hand, we now give a brief review on contact manifolds and Legendrian submanifolds. For some detailed results on contact geometry, please refer to [23]. Let $\pi : PT^*M \longrightarrow M$ be the projective cotangent bundle. This fibration can be considered as a Legendrian fibration with the canonical contact structure $K$. We now review geometric properties of this space. Consider the tangent bundle $\tau : TPT^*M \longrightarrow PT^*M$ and differential map $d\pi : TPT^*M \longrightarrow TM$ of $\pi$. For any $X \in TPT^*M$, there exits an element $\alpha \in T^*M$ such that $\tau(X) = [\alpha]$. For an element $V \in T_xM$, the property $\alpha(V) = 0$ does not depend on the choice of the representative of the class $[\alpha]$. Thus we can define the canonical contact structure on $PT^*M$ by

$$K = \{X \in TPT^*M \mid \tau(X)(d\pi(X)) = 0\}$$

For a local coordinate neighborhood $(U, (x_1, \cdots, x_n))$ on $M$, we have a trivialization

$$PT^*U \cong U \times P(\mathbb{R}^{n-1})^*$$

and we call $((x_1, \cdots, x_n), [\xi_1 : \cdots : \xi_n])$ homogeneous coordinates, where $[\xi_1 : \cdots : \xi_n]$ are homogeneous coordinates of the dual projective space $P(\mathbb{R}^{n-1})^*$. It is easy to show that $X \in K_{(x, \xi)}$ if and only if $\sum_{i=1}^n m_i \xi_i$, where $d\pi(X) = \sum_{\mu=1}^n m_i \frac{\partial}{\partial \xi_i}$. An immersion $i : L \longrightarrow PT^*M$ is said to be a *Legendrian immersion* if $\dim L = n - 1$ and $di_q(T_qL) \subset K_{(q, \xi)}$ for any $q \in L$. We also call the map $\pi \circ i$ the *Legendrian map* and the set $W(i) = \text{image } \pi \circ i$ the *wave front* of $i$. Moreover, $i$ (or, the image of $i$) is called the *Legendrian lift* of $W(i)$.

We now show the basic theorem in this paper which is the fundamental tool for the study of spacelike surfaces in $H^3_1$. We consider the following double fibrations:

(1) $H^3_1 \times H^3_1 \supset \Delta = \{(v, w) \mid \langle v, w \rangle = 0\}$,

(2) $\pi_1 : \Delta \longrightarrow H^3_1$, $\pi_2 : \Delta \longrightarrow H^3_1$,

(3) $\theta_1 = \langle dv, w \rangle \mid \Delta$, $\theta_2 = \langle v, dw \rangle \mid \Delta$.

Where

$$\pi_1(v, w) = v, \quad \pi_2(v, w) = w,$$

$$\langle dv, w \rangle = -w_1 dv_1 - w_2 dv_2 + w_3 dv_3 + w_4 dv_4,$$

$$\langle v, dw \rangle = -v_1 dw_1 - v_2 dw_2 + v_3 dw_3 + v_4 dw_4.$$

The basic theorem in this paper is the following theorem:

**Theorem 2.1** Under the same notations as the above paragraph, each $(\Delta, \theta_i)(i = 1, 2)$ is a contact manifold and both of $\pi_i(i = 1, 2)$ are Legendrian fibrations.

**Proof.** By definition we can easily show that $\Delta$ is a smooth submanifold in $\mathbb{R}^4_2 \times \mathbb{R}^4_2$ and each $\pi_i(i = 1, 2)$ is a smooth fibration.

For any $w = (w_1, w_2, w_3, w_4) \in H^3_1$, we have $w_1 \neq 0$ or $w_2 \neq 0$. Then we can consider a coordinate neighborhood $W^+_1 = \{w = (w_1, w_2, w_3, w_4) \in H^3_1 \mid w_1 > 0\}$ on which we have
\[ w_1 = \sqrt{-w_2^2 + w_3^2 + w_4^2 + 1}. \]

Therefore, we regard \((w_2, w_3, w_4)\) is the local coordinates on \(W^+_1\). We consider a mapping \(\Phi : \Delta(W^+_1) \rightarrow PT^*H^3_1 | W^+_1\) defined by

\[ \Phi(v, w) = (w, [v_1w_2 - v_2w_1 : -v_1w_3 + v_3w_1 : -v_1w_4 + v_4w_1]). \]

Let \(((w_2, w_3, w_4), [\xi_1 : \xi_2 : \xi_3])\) be the homogeneous coordinates of \(PT^*H^3_1\) over \(W^+_1\). We have the canonical contact form \(\theta = \sum_{i=1}^{3} w_{i+1} \xi_i\) on \(PT^*H^3_1\) over \(W^+_1\). It follows that

\[ \Phi^*\theta = (v_1w_2 - v_2w_1)dw_2 + \sum_{i=3}^{4} (-v_1w_i + v_iw_1)dw_i = w_1\langle v, dw \rangle | \Delta(W^+_1) = w_1\theta_2 | W^+_1. \]

This means that \(\theta_2\) is a contact structure such that \(\Phi\) is a contact morphism. We have the similar calculation as the above on the other coordinate neighborhoods. Thus \((\Delta, \theta_2)\) is a contact manifold.

On the other hand, from the fact that \(\langle v, w \rangle = 0\), we have \(\langle dv, w \rangle + \langle v, dw \rangle = 0\). That is \(\langle dv, w \rangle = 0 \iff \langle v, dw \rangle = 0\).

Therefore, both of \(\theta_1\) and \(\theta_2\) give the common contact structure on \(\Delta\). Other assertions are trivial by definition. This completes the proof. \(\square\)

3 The local differential geometry of spacelike surfaces in Anti de Sitter 3-space

In this section we introduce the local differential geometry of spacelike surfaces in Anti de Sitter 3-space.

Let \(X : U \rightarrow H^3_1\) be a regular surface (i.e., an embedding), where \(U \subset \mathbb{R}^2\) is an open subset. We denote \(M = X(U)\) and identify \(M\) with \(U\) through the embedding \(X\). The embedding \(X\) is said to be spacelike if the induced metric \(I\) of \(M\) is Riemannian. Throughout the remain in this paper we assume that \(M\) is a spacelike surface in \(H^3_1\). Since \(\langle X, X \rangle \equiv -1\), we have

\[ \langle X, X_{u_i} \rangle \equiv 0 \ (for \ i = 1, 2), \]

where \(u = (u_1, u_2) \in U\). We define a vector \(e(u)\) by

\[ e(u) = \frac{X(u) \wedge X_{u_1} \wedge X_{u_2}}{\|X(u) \wedge X_{u_1} \wedge X_{u_2}\|}. \]

By definition, we have

\[ \langle e, X_{u_i} \rangle \equiv \langle e, X \rangle \equiv 0, \]

Since \(X\) is timelike and \(X_{u_i} \ (i = 1, 2)\) are spacelike, \(e\) is timelike. Therefore

\[ \langle e, e \rangle \equiv -1. \]

We now define a map 

\[ \mathbb{T} : U \rightarrow H^3_1 \]

by \(\mathbb{T}(u) = e(u)\) which is called the timelike Anti de Sitter Gauss image (briefly, TAdS-Gauss image) of \(X\) (or \(M\)).

We now consider the geometric meanings of the TAdS-Gauss image of a spacelike surface. We have the following proposition.
Proposition 3.1 Let $X : U \rightarrow H^3_1$ be a spacelike surface in Anti de Sitter 3-space. If the TAdS-Gauss image $T$ is constant, then the spacelike surface $X(U) = M$ is a part of a AdS-great-hyperboloid.

Proof. We consider the set $V = \{y \in \mathbb{R}^2_1 | \langle y, e \rangle = 0 \}$. Since $T = e$ is constant, the set $V = HP(e, 0)$ is a Lorentz hyperplane. We also have $\langle X, e \rangle = 0$, so $X(U) = M \subset V \cap H^3_1$. □

It is easy to show that $T_{u_i} (i = 1, 2)$ are tangent vectors of $M$. Therefore we have a linear transformation $W_p = -dT(u) : T_p M \rightarrow T_p M$ which is called the Anti de Sitter shape operator (briefly, AdS-shape operator) of $M = X(U)$ at $p = X(u)$. We denote the eigenvalue of $W_p$ by $k_i(p)$ ($i = 1, 2$).

The Anti de Sitter Gauss-Kronecker curvature (briefly, AdS-G-K curvature) of $M = X(U)$ at $p = X(u)$ is defined to be

$$K_{AdS}(u) = \det W_p = k_1(p) \cdot k_2(p).$$

We say that a point $p = X(u)$ is an Anti de Sitter parabolic point (or, briefly an AdS-parabolic point) of $X : U \rightarrow H^3_1$ if $K_{AdS}(u) = 0$.

We say that a point $u \in U$ or $p = X(u)$ is an umbilic point if $W_p = k(p)id_{T_p M}$. We also say that $M = X(U)$ is totally umbilic if all points on $M$ are umbilic. Then we have the following proposition.

Proposition 3.2 Suppose that $M = X(U)$ is totally umbilic. Then $k(p)$ is constant $k$. Under this condition, we have the following classification.

1. If $k \neq 0$ then $M$ is a part of a AdS-hyperboloid $HP(n, -1) \cap H^3_1$, where $n = X + \frac{1}{k}e$ is a constant timelike vector.

2. If $k = 0$ then $M$ is a part of a AdS-flat hyperboloid $HP(n, 0) \cap H^3_1$, where $n = e$ is a constant timelike vector.

Proof. By definition, we have $-T_{u_i} = kX_{u_i}$ for $i = 1, 2$. Therefore we have

$$-T_{u_i u_j} = k_{u_i}X_{u_i} + kX_{u_i u_j}$$

Since $-T_{u_i u_j} = -T_{u_j u_i}$ and $kX_{u_i u_j} = kX_{u_j u_i}$, we have $k_{u_j}X_{u_i} = k_{u_i}X_{u_j}$. From the fact $\{X_{u_1}, X_{u_2}\}$ is linearly independent, so that $k$ is a constant.

We now assume that $k \neq 0$. Since $-T_{u_i} = -e_{u_i} = kX_{u_i}$, there exists a constant vector $n$ such that $X = n - \frac{e}{k}$. We can calculate that

$$\langle n, n \rangle = \langle X + \frac{e}{k}, X + \frac{e}{k} \rangle = -1 - \frac{1}{k^2} < 0,$$

and

$$\langle X, n \rangle = \langle X, X + \frac{e}{k} \rangle = -1.$$ 

This means that $M = X(U) \subset HP(n, -1) \cap H^3_1$, so in this case the assertion follows.

If $k = 0$. Then $T = e = n$. in this case the assertion follow from the Proposition 3.1. This completes the proof. □

Since $X_{u_1}$ and $X_{u_2}$ are spacelike vectors, we first introduce the Riemannian metric $ds^2 = \sum_{i,j=1}^2 g_{ij} du_i du_j$ on $M = X(U)$, where $g_{ij}(u) = \langle X_{u_i}(u), X_{u_j}(u) \rangle$ for any $u \in U$. We also define the Anti de Sitter second fundamental invariant by $h_{ij}(u) = \langle -T_{u_i}(u), X_{u_j}(u) \rangle$ for any $u \in U$. We have the following results similar to the results of [6].

Proposition 3.3 With the above notation, we have the following Anti de Sitter Wein-
garten formula:

\[ T_{ui} = \sum_{j=1}^{2} h^j_i X_{uj}, \]

where \((h^j_i) = (h_{ik})(g^{kj})\) and \((g^{kj}) = (g_{kj})^{-1}\).

**Proof.** There exist real numbers \(\alpha, \beta, \lambda^j_i\) such that

\[ T_{ui} = \alpha X + \beta e + \sum_{j=1}^{2} \lambda^j_i X_{uj}. \]

Since \(\langle T, X \rangle = 0\), \(\langle T, X_{ui} \rangle = 0\), \(\langle T, T \rangle = -1\), we have

\[ 0 = \langle T_{ui}, X \rangle = -\alpha, \quad 0 = \langle T_{ui}, T \rangle = -\beta. \]

Therefore, we have

\[ T_{ui} = \sum_{j=1}^{2} \lambda^j_i X_{uj}. \]

By definition, we have

\[ -h_{ik} = \langle T_{ui}, X_{uk} \rangle = \sum_{l=1}^{2} \lambda^j_l g_{lk}. \]

Hence, we have

\[ -h^j_i = -\sum_{l=1}^{2} h_{ik} g^{kj} = \lambda^j_i. \]

This completes the proof of the AdS-weingarten formula. \(\Box\)

As a corollary of the above proposition, we have an explicit expression for the AdS-G-K curvature by Riemannian metric and the Anti de Sitter second fundamental invariant.

**Corollary 3.4** With the same notation as in the above Proposition, we can give the AdS-G-K curvature as follows:

\[ K_{AdS} = \frac{\det(h_{ij})}{\det(g_{ij})}. \]

Since \(ds^2\) is a Riemannian metric, we have the section curvature \(K_I\) of \(M\), which we call an intrinsic Gaussian curvature. By B. O’Neil [22] (Page 107 Corollary 20), we remark that \(K_{AdS} = -1 - K_I\).

4 The timelike Anti de Sitter height function

In this section we define a family of functions on a spacelike surface in Anti de Sitter 3-space which is useful for the study of singularities of TAdS-Gauss image.

Let \(X : U \rightarrow H^3_1\) be a spacelike surface. We define a family of functions

\[ H : U \times H^3_1 \rightarrow \mathbb{R} \]

by \(H(u, v) = \langle X(u), v \rangle\). We call \(H\) a timelike Anti de Sitter height function (or, a AdS-height function) on \(M = X(U)\). We denote the Hessian matrix of the AdS-height function
\( h_{v_0}(u) = H(u, v_0) \) at \( u_0 \) by \( \text{Hess}(h_{v_0})(u_0) \). Then we have the following proposition.

**Proposition 4.1** Let \( M = X(U) \) be a spacelike surface in \( H^3_1 \) and \( H : U \times H^3_1 \to \mathbb{R} \) be a AdS-height function. Then we have the following assertions:

1. \( H(u, v) = \frac{\partial H}{\partial u_1}(u, v) = 0 \) (for \( i = 1, 2 \)) if and only if \( v = \pm e(u) = \pm \mathbb{T}(u) \);
2. Let \( v_0 = e(u_0) \), then \( \text{detHess}(h_{v_0})(u_0) = 0 \) if and only if \( K_{\text{AdS}}(u_0) = 0 \).

**Proof.** (1) Since \( \{ X, e, X_{u_1}, X_{u_2} \} \) is a basis of the vector space \( T_p \mathbb{R}^4_2 \) where \( p = X(u) \), there exist real numbers \( \lambda, \eta, \alpha_1, \alpha_2 \) such that \( v = \lambda X + \eta e + \alpha_1 X_{u_1} + \alpha_2 X_{u_2} \). Therefore \( H(u, v) = 0 \) if and only if \( \lambda = -\langle X(u), v \rangle = 0 \). Since \( 0 = \frac{\partial H}{\partial u_2}(u, v) = \langle X_{u_2}, v \rangle = \sum_{j=1}^{2} g_{ij} \alpha_j \). Since \( (g_{ij}) \) is non-degenerate, we have \( \alpha_i = 0 \) (for \( i = 1, 2 \)). Therefore we have \( v = \eta e \). Then from a straight forward calculation, we have \( \eta = \pm 1 \).

(2) By definition, we have

\[
\text{Hess}(h_{v_0})(u_0) = (\langle X_{u_1 u_2}(u_0), \mathbb{T}(u_0) \rangle) = (\langle X_{u_1}(u_0), \mathbb{T}_{u_1}(u_0) \rangle). 
\]

By the AdS-Weingarten formula, we have

\[
-\langle X_{u_1}, \mathbb{T}_{u_1} \rangle = \sum_{a=1}^{2} h_{i}^{a} \langle X_{u_a}, X_{u_j} \rangle = \sum_{a=1}^{2} h_{i}^{a} g_{a j} = h_{i j}. 
\]

Therefore we have

\[
K_{\text{AdS}} = \frac{\text{det}(h_{i j})}{\text{det}(g_{a \beta})} = \frac{\text{detHess}(h_{v_0})(u_0)}{\text{det}(g_{a \beta}(u_0))}. 
\]

Then we complete the proof. \( \square \)

As an application of the above proposition, we have the following.

**Corollary 4.2** Let \( H : U \times H^3_1 \to \mathbb{R} \), with \( H(u, v) = h_v(u) \) be a AdS-height function on spacelike surface \( M = X(U) \) and \( \mathbb{T} \) be the TAdS-Gauss image, \( p = X(u) \). Then the following conditions are equivalent:

1. \( \exists v \in H^3_1 \), such that \( p \in M \) is a degenerate singular point of AdS-height function \( h_v \);
2. \( \exists v \in H^3_1 \), such that \( p \in M \) is a singular point of TAdS-Gauss image \( \mathbb{T} \);
3. \( K_{\text{AdS}}(u) = 0 \).

**Proof.** By definition, (2) and (3) are equivalent. By the assertion (2) of above proposition, we have (1) and (3) are also equivalent. \( \square \)

5 TAdS-Gauss images as Legendrian maps

In this section we naturally interpret the TAdS-Gauss image \( \mathbb{T} \) of \( M \) as a Legendrian map in the framework of Legendrian singularity theory. We give a brief review on Legendrian singularity theory mainly due to Arnold [1]. The main tool of Legendrian singularities theory is the notion of generating families. Let \( F : (\mathbb{R}^k \times \mathbb{R}^n, 0) \to (\mathbb{R}, 0) \) be a function germ. We say that \( F \) is a Morse family if the mapping

\[
\Delta^*F = (F, \frac{\partial F}{\partial q_1}, \ldots, \frac{\partial F}{\partial q_k}) : (\mathbb{R}^k \times \mathbb{R}^n, 0) \to (\mathbb{R} \times \mathbb{R}^k, 0) 
\]

is a Morse family.
is non-singular, where \((q, x) = (q_1, \cdots, q_k, x_1, \cdots, x_n) \in (\mathbb{R}^k \times \mathbb{R}^n, 0)\). In this case we have a smooth \((n - 1)\)-dimensional submanifold,

\[
\Sigma_s(F) = \{(q, x) \in (\mathbb{R}^k \times \mathbb{R}^n, 0) | F(q, x) = \frac{\partial F}{\partial q_1}(q, x) = \cdots = \frac{\partial F}{\partial q_k}(q, x) = 0\}
\]

and the map germ \(\Phi_F: (\Sigma_s(F), 0) \rightarrow P^*\mathbb{R}^n\) defined by

\[
\Phi_F(q, x) = (x, [\frac{\partial F}{\partial x_1}(q, x) : \cdots : \frac{\partial F}{\partial x_n}(q, x)])
\]

is a Legendrian immersion germ. Then we have the following fundamental theorem of Arnold [1] and Zakalyukin [20].

**Proposition 5.1** All Legendrian submanifold germs in \(P^*\mathbb{R}^n\) are constructed by the above method.

We call \(F\) a generating family of \(\Phi_F(\Sigma_s(F))\). Therefore the corresponding wave front is

\[
W(\Phi_F) = \{x \in \mathbb{R}^n | \exists q \in \mathbb{R}^k \text{ such that } F(q, x) = \frac{\partial F}{\partial q_1}(q, x) = \cdots = \frac{\partial F}{\partial q_k}(q, x) = 0\}.
\]

We sometimes denote \(\mathcal{D}_F = W(\Phi_F)\) and call it the discriminant set of \(F\).

Now we can apply the above arguments to our situation. Let \(X : U \rightarrow H^3_1\) be a spacelike surface in \(H^3_1\) and \(\mathcal{T}\) be the TAdS-Gauss image on \(M = X(U)\). We define a mapping

\[
\mathcal{L} : U \rightarrow \Delta
\]

by \(\mathcal{L}(u) = (X(u), \mathcal{T}(u))\). Since \(\langle X(u), \mathcal{T}(u) \rangle = \langle dX(u), \mathcal{T}(u) \rangle = 0\), the mapping \(\mathcal{L}\) is a Legendrian embedding. We denote \(X(u) = (x_1, x_2, x_3, x_4)\) and \(\mathcal{T}(u) = (v_1, v_2, v_3, v_4)\) as coordinate representations. We define a smooth mapping

\[
\mathcal{T} : U \rightarrow P^*(H^3_1)
\]

by \(\mathcal{T}(u) = (\mathcal{T}(u), [(x_1v_2 - x_2v_1) : (-x_1v_3 + x_3v_1) : (-x_1v_4 + x_4v_1)])\).

**Proposition 5.2** The AdS-height function \(H : U \times H^3_1 \rightarrow \mathbb{R}\) is a Morse family.

**Proof.** For any \(u = (v_1, v_2, v_3, v_4) \in H^3_1\), we have \(v_1 \neq 0\) or \(v_2 \neq 0\). Without loss of the generality, we might assume that \(v_1 > 0\), then \(v_1 = \sqrt{1 + v_3^2 + v_4^2 - v_2^2}\). So that

\[
H(u, v) = -x_1(u)\sqrt{1 + v_3^2 + v_4^2 - v_2^2} + x_2(u)v_2 + x_3(u)v_3 + x_4(u)v_4
\]

where \(X(u) = (x_1(u), x_2(u), x_3(u), x_4(u))\). We have to prove the mapping

\[
\Delta^*H = (H, \frac{\partial H}{\partial u_1}, \frac{\partial H}{\partial u_2})
\]

is non-singular at any point. The Jacobian matrix of \(\Delta^*H\) is given as follows:

\[
\begin{pmatrix}
\langle X_{u_1}, v \rangle & \langle X_{u_2}, v \rangle & x_1 \frac{\partial x_2}{\partial v_1} - x_2 & -x_1 \frac{\partial x_3}{\partial v_1} + x_3 & -x_1 \frac{\partial x_4}{\partial v_1} + x_4 \\
\langle X_{u_1u_1}, v \rangle & \langle X_{u_1u_2}, v \rangle & x_{1u_1} \frac{\partial x_2}{\partial v_1} - x_{2u_1} & -x_{1u_1} \frac{\partial x_3}{\partial v_1} + x_{3u_1} & -x_{1u_1} \frac{\partial x_4}{\partial v_1} + x_{4u_1} \\
\langle X_{u_2u_1}, v \rangle & \langle X_{u_2u_2}, v \rangle & x_{1u_2} \frac{\partial x_2}{\partial v_1} - x_{2u_2} & -x_{1u_2} \frac{\partial x_3}{\partial v_1} + x_{3u_2} & -x_{1u_2} \frac{\partial x_4}{\partial v_1} + x_{4u_2}
\end{pmatrix}.
\]

We claim that it will suffice to show that the determinant of the matrix

\[
A = \begin{pmatrix}
x_1 \frac{\partial x_2}{\partial v_1} - x_2 & -x_1 \frac{\partial x_3}{\partial v_1} + x_3 & -x_1 \frac{\partial x_4}{\partial v_1} + x_4 \\
x_{1u_1} \frac{\partial x_2}{\partial v_1} - x_{2u_1} & -x_{1u_1} \frac{\partial x_3}{\partial v_1} + x_{3u_1} & -x_{1u_1} \frac{\partial x_4}{\partial v_1} + x_{4u_1} \\
x_{1u_2} \frac{\partial x_2}{\partial v_1} - x_{2u_2} & -x_{1u_2} \frac{\partial x_3}{\partial v_1} + x_{3u_2} & -x_{1u_2} \frac{\partial x_4}{\partial v_1} + x_{4u_2}
\end{pmatrix},
\]

is non-singular at any point.
does not vanish at \((u, v) \in \Delta^*H^{-1}(0)\). In this case, \(v = T(u)\) and we denote
\[
b_1 = \begin{pmatrix} x_1 \\ x_{1u_1} \\ x_{1u_2} \end{pmatrix}, \quad b_2 = \begin{pmatrix} x_2 \\ x_{2u_1} \\ x_{2u_2} \end{pmatrix}, \quad b_3 = \begin{pmatrix} x_3 \\ x_{3u_1} \\ x_{3u_2} \end{pmatrix}, \quad b_4 = \begin{pmatrix} x_4 \\ x_{4u_1} \\ x_{4u_2} \end{pmatrix}.
\]
Then we have
\[
\det A = \frac{-v_1}{v_1} \det(b_2 b_3 b_4) + \frac{v_2}{v_1} \det(b_1 b_3 b_4) - \frac{v_3}{v_1} \det(b_1 b_2 b_4) + \frac{v_4}{v_1} \det(b_1 b_2 b_3).
\]
On the other hand, we have
\[
X \wedge X_{u_1} \wedge X_{u_2} = (-\det(b_2 b_3 b_4), \det(b_1 b_3 b_4), \det(b_1 b_2 b_4), -\det(b_1 b_2 b_3))
\]
Therefore we have
\[
\det A = \frac{1}{v_1} (\langle T, \| X \wedge X_{u_1} \wedge X_{u_2} \| e \rangle)
\]
\[
= \| X \wedge X_{u_1} \wedge X_{u_2} \| / v_1 \neq 0.
\]
We now show that \(H\) is a generating family of \(\mathcal{L}(U) \subset \Delta\).

**Proposition 5.3** For any spacelike surfaces \(X : U \rightarrow H^3_1\), the AdS-height function \(H : U \times H^3_1 \rightarrow \mathbb{R}\) of \(X\) is a generating family of the Legendrian embedding \(\mathcal{L}\).

**Proof.** We consider a coordinate neighborhood \(W^+_1 = \{ w = (w_1, w_2, w_3, w_4) \in H^3_1 \mid w_1 > 0 \}\). Remember the contact morphism \(\Phi : \Delta(W^+_1) \rightarrow PT^*H^3_1 \mid W^+_1\) defined in the proof of Theorem 2.1. Since AdS-height function \(H\) is a Morse family, we have a Legendrian immersion
\[
\mathcal{L}_H : \Sigma_s(H) \mid (U \times W^+_1) \rightarrow PT^*H^3_1 \mid W^+_1
\]
defined by
\[
\mathcal{L}_H(u, w) = (w, [\frac{\partial H}{\partial w_2}, \frac{\partial H}{\partial w_3}, \frac{\partial H}{\partial w_4}]).
\]
By Proposition 4.1, we have
\[
\Sigma_s(H) = \{(u, T(u)) \in U \times H^3_1 \mid u \in U\}.
\]
Since \(w = T(u)\) and \(w_1 = \sqrt{-w_2^2 + w_3^2 + w_4^2 + 1}\), we have
\[
\frac{\partial H}{\partial w_2}(u, T(u)) = x_1(u) \frac{v_2(u)}{v_1(u)} - x_2(u),
\]
\[
\frac{\partial H}{\partial w_3}(u, T(u)) = x_3(u) - x_1(u) \frac{v_3(u)}{v_1(u)},
\]
\[
\frac{\partial H}{\partial w_4}(u, T(u)) = x_4(u) - x_1(u) \frac{v_4(u)}{v_1(u)},
\]
where \(X = (x_1, x_2, x_3, x_4)\) and \(T = (v_1, v_2, v_3, v_4)\). It follows that
\[
\mathcal{L}_H(u, T(u)) = (T(u), [x_1 v_2 - x_2 v_1 : -x_1 v_3 + x_3 v_1 : -x_1 v_4 + x_4 v_1]) = T(u).
\]
Therefore we have \(\Phi \circ \mathcal{L}(u) = T(u)\) on \(W^+_1\). We also have the same relation as the above on the other local coordinates. This means that \(H\) is a generating family of \(\mathcal{L} \subset \Delta\).

Therefore we conclude that the TAdS-Gauss image \(T\) can be regarded as a Legendrian map.
6 Contact with AdS-great-hyperboloids

In this section we consider the geometric meaning of the singularities of the TAdS-Gauss image of spacelike surface $M = X(U)$ in $H^3_1$. We consider the contact of spacelike surfaces with AdS-great-hyperboloids. We now briefly review the theory of contact due to Montaldi [16]. Let $X_i, Y_i (i = 1, 2)$ be submanifolds of $\mathbb{R}^n$ with $\dim X_1 = \dim X_2$ and $\dim Y_1 = \dim Y_2$. We say that the contact of $X_1$ and $Y_1$ at $y_1$ is the same type as the contact of $X_2$ and $Y_2$ at $y_2$ if there is a diffeomorphism germ $\Phi: (\mathbb{R}^n, y_1) \to (\mathbb{R}^n, y_2)$ such that $\Phi(X_1) = X_2$ and $\Phi(Y_1) = Y_2$. In this case we write $K(X_1, Y_1; y_1) = K(X_2, Y_2; y_2)$. It is clear that in the definition $\mathbb{R}^n$ could be replaced by any manifold. In his paper [16], Montaldi gives a characterization of the notion of contact by using the terminology of singularity theory.

**Theorem 6.1** Let $X_i, Y_i (i = 1, 2)$ be submanifolds of $\mathbb{R}^n$ with $\dim X_1 = \dim X_2$ and $\dim Y_1 = \dim Y_2$. Let $g_i: (X_i, x_i) \to (\mathbb{R}^n, y_i)$ be immersion germs and $f_i: (\mathbb{R}^n, y_i) \to (\mathbb{R}^p, 0)$ be submersion germs with $(Y_i, y_i) = (f_i^{-1}(0), y_i)$. Then $K(X_1, Y_1; y_1) = K(X_2, Y_2; y_2)$ if and only if $f_1 \circ g_1$ and $f_2 \circ g_2$ are $K$-equivalent.

For the definition of the $K$-equivalent, See Martinet [15]. We now consider a function $H: H^3_1 \times H^3_1 \to H^3_1$ defined by $H(u, v) = (u, v)$. For any $v_0 \in H^3_1$, we denote $h_{v_0} = H(v_0)$ and we have the AdS-great-hyperboloid $h_{v_0}^{-1}(0) = H^3_1 \cap HP(v_0, 0)$. We write $AH(v_0, 0) = H^3_1 \cap HP(v_0, 0)$. For any $u_0 \in U$, we consider the timelike vector $v_0 = T(u_0)$. Then we have

$$h_{v_0} \circ X(u_0) = H \circ (X \times id_{H^3_1})(u_0, v_0) = H(u_0, T(u_0)) = 0.$$

We also have relations

$$\frac{\partial h_{v_0} \circ X}{\partial u_i}(u_0) = \frac{\partial H}{\partial u_i}(u_0, T(u_0)) = 0,$$

for $i = 1, 2$. This means that the AdS-great-hyperboloid $AH(v_0, 0)$ is tangent to $M = X(U)$ at $p = X(u_0)$. In this case, we call $AH(v_0, 0)$ the tangent AdS-great-hyperboloid of $M = X(U)$ at $p = X(u_0)$ (or, $u_0$), which we write $AH(X, u_0)$. Let $v_1, v_2$ be timelike vectors. If $v_1$ and $v_2$ are linearly dependent, then $HP(v_1, 0)$ and $HP(v_2, 0)$ are equal. Therefore, AdS-great-hyperboloids $AH(v_1, 0) = AH(v_2, 0)$. Then we have the following simple lemma.

**Lemma 6.2** Let $X : U \to H^3_1$ be a spacelike surface. Consider two points $u_1, u_2 \in U$. Then we have the following assertion:

$$T(u_1) = T(u_2) \text{ if and only if } AH(X, u_1) = AH(X, u_2). \square$$

We now consider the contact of $M$ with tangent AdS-great-hyperboloid at $p \in M$ as an application of Legendrian singularity theory. We introduce an equivalence relation among Legendrian immersion germs. Let $i: (L, p) \subset (PT^*\mathbb{R}^n, p)$ and $i': (L', p') \subset (PT^*\mathbb{R}^n, p')$ be Legendrian immersion germs. Then we say that $i$ and $i'$ are Legendrian equivalent if there exists a contact diffeomorphism germ $H: (PT^*\mathbb{R}^n, p) \to (PT^*\mathbb{R}^n, p')$ such that $H$ preserves fibres of $\pi$ and that $H(L) = L'$. A Legendrian germ into $PT^*\mathbb{R}^n$ at a point is said to be Legendrian stable if for every map with the given germ there are a neighbourhood in the space of Legendrian immersion (in the Whitney $C^\infty$—topology) and a neighbourhood of the original point such that each Legendrian immersion belonging to the first neighbourhood has, in the second neighbourhood, a point at which its germ is Legendrian equivalent to the original germ.

Since the Legendrian lift $i: (L, p) \subset (PT^*\mathbb{R}^n, p)$ is uniquely determined on the regular part of the wave front $W(i)$, we have the following simple but significant property of Legendrian
Proposition 6.3 Let $i : (L, p) \subset (PT^*\mathbb{R}^n, p)$ and $i' : (L', p') \subset (PT^*\mathbb{R}^n, p')$ be Legendrian immersion germs such that regular sets of $\pi \circ i$ and $\pi \circ i'$ respectively are dense. Then $i$ and $i'$ are Legendrian equivalent if and only if wave front sets $W(i)$ and $W(i')$ are diffeomorphic as set germs.

This result had been firstly pointed out by Zakalyukin [21]. The assumption in the above proposition is a generic condition for $i$ and $i'$. In particular, if $i$ and $i'$ are Legendrian stable, then these satisfy the assumption.

We can interpret the Legendrian equivalence by using the notion of generating families. We denote $\mathcal{E}_n$ the local ring of function germs $(\mathbb{R}^n, 0) \to \mathbb{R}$ with the unique maximal ideal $\mathcal{M}_n = \{ h \in \mathcal{E}_n | h(0) = 0 \}$. Let $F, G : (\mathbb{R}^k \times \mathbb{R}^n, 0) \to (\mathbb{R}, 0)$ be function germs. We say that $F$ and $G$ are $P-K$ equivalent if there exists a diffeomorphism germ $\Psi : (\mathbb{R}^k \times \mathbb{R}^n, 0) \to (\mathbb{R}^k \times \mathbb{R}^n, 0)$ of the form $\Psi(q, x) = (\psi_1(q, x), \psi_2(x))$ for $(q, x) \in (\mathbb{R}^k \times \mathbb{R}^n, 0)$ such that $\Psi^*\langle (F)_{\mathcal{E}_{k+n}} \rangle = \langle G \rangle_{\mathcal{E}_{k+n}}$. Here $\Psi^* : \mathcal{E}_{k+n} \to \mathcal{E}_{k+n}$ is the pull back $\mathbb{R}$-algebra isomorphism defined by $\Psi^*(h) = h \circ \Psi$.

Let $F : (\mathbb{R}^k \times \mathbb{R}^n, 0) \to (\mathbb{R}, 0)$ be a function germ. We say that $F$ is a $K$-versal deformation of $f = F|\mathbb{R}^k \times \{0\}$ if

$$\mathcal{E}_k = T_e(K)(f) + \langle \frac{\partial F}{\partial x_1}|_{\mathbb{R}^k \times \{0\}}, \cdots, \frac{\partial F}{\partial x_n}|_{\mathbb{R}^k \times \{0\}} \rangle_{\mathbb{R}}$$

where

$$T_e(K)(f) = (\frac{\partial f}{\partial q_1}, \cdots, \frac{\partial f}{\partial q_k}, f)_{\mathcal{E}_k}.$$ 

The main result in the theory of Arnold [1] and Zakalyukin [20] is the following:

Theorem 6.4 Let $F, G : (\mathbb{R}^k \times \mathbb{R}^n, 0) \to (\mathbb{R}, 0)$ be Morse families. Then

1. $\Phi_F$ and $\Phi_G$ are Legendrian equivalent if and only if $F$ and $G$ are $P-K$ equivalent;
2. $\Phi_F$ is Legendrian stable if and only if $F$ is a $K$-versal deformation of $f = F|\mathbb{R}^k \times \{0\}$.

Since $F$ and $G$ are function germs on the common space germ $(\mathbb{R}^k \times \mathbb{R}^n, 0)$, we do not need the notion of stably $P-K$ equivalences under this situation (cf., [1]). By the uniqueness result of the $K$-versal deformation of a function germ, Proposition 6.3 and Theorem 6.4, we have the following classification result of Legendrian stable germs (cf. [3]). For any map germ $f : (\mathbb{R}^n, 0) \to (\mathbb{R}^p, 0)$, we define the local ring of $f$ by $Q(f) = \mathcal{E}_n/f^*(\mathcal{M}_p)\mathcal{E}_n$.

Proposition 6.5 Let $F, G : (\mathbb{R}^k \times \mathbb{R}^n, 0) \to (\mathbb{R}, 0)$ be Morse families. Suppose that $\Phi_F$ and $\Phi_G$ are Legendrian stable. Then the following conditions are equivalent:

1. $(W(\Phi_F)_0)$ and $(W(\Phi_G)_0)$ are diffeomorphic as germs;
2. $\Phi_F$ and $\Phi_G$ are Legendrian equivalent;
3. $Q(f)$ and $Q(g)$ are isomorphic as $\mathbb{R}$-algebras, where $f = F|\mathbb{R}^k \times \{0\}$ and $g = G|\mathbb{R}^k \times \{0\}$.

Proof. See [6] \hfill \Box

We have the tools for study of the contact of spacelike surfaces with AdS-great-hyperboloids.

Let $\mathbb{T}_i : (U, u_i) \to (H^3_1, v_i)$ (for $i = 1, 2$) be TAdS-Gauss image germs of spacelike surface germs $X_i : (U, u_i) \to (H^3_1, X_i(u_i))$. We say that $\mathbb{T}_1$ and $\mathbb{T}_2$ are $\mathcal{A}$-equivalent if there exist diffeomorphism germs $\phi : (U, u_1) \to (U, u_2)$ and $\Phi : (H^3_1, v_1) \to (H^3_1, v_2)$ such that $\phi \circ \mathbb{T}_1 = \mathbb{T}_2 \circ \phi$. 

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Suppose the regular set of $T_i$ is dense in $(U, u_i)$ for each $i = 1, 2$. It follows from Proposition 6.3 that $T_1$ and $T_2$ are $\mathcal{A}$-equivalent if and only if the corresponding Legendrian embedding germs $\mathcal{L}^1 : (U, u_1) \longrightarrow (\Delta, z_1)$ and $\mathcal{L}^2 : (U, u_2) \longrightarrow (\Delta, z_2)$ are Legendrian equivalent. This condition is also equivalent to the condition that two generating families $H_1$ and $H_2$ are $P-K$ equivalent by Theorem 6.4. Here, $H_i : (U \times H^3_i, (u_i, v_i)) \longrightarrow \mathbb{R}$ is the corresponding AdS-height function germ of $X_i$.

On the other hand, we denote $h_{i,v_i} = H_i(u, v_i)$; then we have $h_{i,v_i}(u) = h_{v_i} \circ X_i(u)$. By Theorem 6.1, 

$$K(X_1(U), AH(X_1, u_1), v_1) = K(X_2(U), AH(X_2, u_2), v_2)$$

if and only if $h_{1,v_1}$ and $h_{2,v_2}$ are $K$-equivalent. Therefore, we can apply the above arguments to our situation. We denote by $Q(x, u_0)$ the local ring of the function germ $h_{u_0} : (U, u_0) \longrightarrow \mathbb{R}$, where $v_0 = T(u_0)$. We remark that we can write the local ring explicitly as follows:

$$Q(x, u_0) = \frac{C_{u_0}^\infty(U)}{\langle (X(u), T(u_0)) \rangle_{C_{u_0}^\infty(U)}},$$

where $C_{u_0}^\infty(U)$ is the local ring of function germs at $u_0$ with the unique maximal ideal $\mathcal{M}_{u_0}(U)$.

**Theorem 6.6** Let $X_i : (U, u_i) \longrightarrow (H^3_i, X_i(u_i))$ (for $i = 1, 2$) be spacelike surface germs such that the corresponding Legendrian embedding germs $\mathcal{L}^i : (U, u_i) \longrightarrow (\Delta, z_i)$ are Legendrian stable. Then the following conditions are equivalent:

1. $TAdS$-Gauss image germs $T_1$ and $T_2$ are $\mathcal{A}$-equivalent;
2. $H_1$ and $H_2$ are $P-K$-equivalent;
3. $h_{1,v_1}$ and $h_{2,v_2}$ are $K$-equivalent;
4. $K(X_1(U), AH(X_1, u_1), v_1) = K(X_2(U), AH(X_2, u_2), v_2)$
5. $Q(X_1, u_1)$ and $Q(X_2, u_2)$ are isomorphic as $\mathbb{R}$-algebras.

**Proof.** By the previous arguments (mainly from Theorem 6.1), it has already been shown that conditions (3) and (4) are equivalent. Other assertions follow from Proposition 6.5. □

For a spacelike surface germ 

$$X : (U, u_0) \longrightarrow (H^3_1, X(u_0)),$$

we call $X^{-1}(AH(T(u_0), 0), u_0)$ the tangent $AdS$-great-hyperboloid indicatrix germ of $X$. In general we have the following proposition:

**Proposition 6.7** Let $X_i : (U, u_i) \longrightarrow (H^3_i, X_i(u_i))$ (for $i = 1, 2$) be spacelike surface germs such that their $AdS$-parabolic sets have no interior points as subspaces of $U$. If $TAdS$-Gauss image germs $T_1$ and $T_2$ are $\mathcal{A}$-equivalent, then 

$$K(X_1(U), AH(X_1, u_1), v_1) = K(X_2(U), AH(X_2, u_2), v_2).$$

In this case, $X_1^{-1}(AH(T_1(u_1), 0), u_1)$ and $X_2^{-1}(AH(T_2(u_2), 0), u_2)$ are diffeomorphic as set germs.

**Proof.** The AdS-parabolic set is the set of singular points of the $TAdS$-Gauss image. So the corresponding Legendrian embedding $\mathcal{L}^i$ satisfy the hypothesis of Proposition 6.3. If $TAdS$-Gauss image germs $T_1$ and $T_2$ are $\mathcal{A}$-equivalent, then $\mathcal{L}^1$ and $\mathcal{L}^2$ are Legendrian equivalent, so that $H_1$ and $H_2$ are $P-K$-equivalent. Therefore, $h_{1,v_1}$ and $h_{2,v_2}$ are $K$-equivalent. By
Theorem 5.1, this condition is equivalent to the condition that $K(X_1(U), AH(X_1, u_1, v_1)) = K(X_2(U), AH(X_2, u_2, v_2))$.

On the other hand, we have $X_i^{-1}(AH(T_i(u_0), 0), u_0) = (h_i^{-1}(0), u_0)$. It follows from this fact that $X_i^{-1}(AH(T_1(u_1), 0), u_1)$ and $X_2^{-1}(AH(T_2(u_2), 0), u_2)$ are diffeomorphic as set germs because the $\mathcal{K}$-equivalent preserves the zero level sets.

From the above proposition, the diffeomorphism type of the tangent AdS-great-hyperboloid indicatrix germ is an invariant of $\mathcal{A}$-classification of the TAdS-Gauss image germ of $X$. Moreover, we can borrow some basic invariants from the singularity theory on function germs. We need $\mathcal{K}$-invariants for a function germ. The local ring of a function is a complete $\mathcal{K}$-invariant for generic function germs. It is, however, not a numerical invariant. The $\mathcal{K}$-codimension of a function germ is a numerical $\mathcal{K}$-invariant of function germs. We denote

$$\text{AdS-ord}(X, u_0) = \dim \frac{C^\infty_{\nu_0}(U)}{(h_{\nu_0}, \partial h_{\nu_0}/\partial u_0)C^\infty_{\nu_0}(U)},$$

where $\nu_0 = \mathbb{T}(u_0)$. Usually $\text{AdS-ord}(X, u_0)$ is called the $\mathcal{K}$-codimension of $h_{\nu_0}$. However, We call it the order of contact with tangent AdS-great-hyperboloid at $X(u_0)$. We also have the notion of corank of function germs:

$$\text{AdS-corank}(X, u_0) = 2 - \text{rank Hess}(h_{\nu_0})(u_0),$$

where $\nu_0 = \mathbb{T}(u_0)$.

By Proposition 4.1, $X(u_0)$ is an AdS-parabolic point if and only if $\text{AdS-corank}(X, u_0) \geq 1$. On the other hand, a function germ $f : (\mathbb{R}^{n-1}, a) \rightarrow \mathbb{R}$ has the $A_k$-type singularity if $f$ is $\mathcal{K}$-equivalent to the germ $\pm u_1^2 \pm \cdots \pm u_{n-2}^2 + u_{n-1}^{k+1}$. If $\text{AdS-corank}(X, u_0) = 1$, the AdS-height function $h_{\nu_0}$ has the $A_k$-type singularity at $u_0$ and is generic. In this case we have $\text{AdS-ord}(X, u_0) = k$. This number is equal to the order of contact in the classical sense (cf., [2]). This is the reason why we call $\text{AdS-ord}(X, u_0)$ the order of contact with the AdS-great-hyperboloid at $X(u_0)$.

7 Generic properties

In this section we consider generic properties of spacelike surfaces in $H^3_1$. The main tool is a kind of transversality theorem. We consider the space of spacelike embeddings $\text{Embs}(U, H^3_1)$ with Whitney $C^\infty$-topology. We also consider the function $\mathcal{H} : H^3_1 \times H^3_1 \rightarrow \mathbb{R}$ which is given in §6. We claim that $\mathcal{H}_u$ is a submersion for any $u \in H^3_1$, where $\mathcal{H}_u(v) = \mathcal{H}(u, v)$. For any $X \in \text{Embs}(U, H^3_1)$, we have $H = \mathcal{H}o(X \times id_{H^3_1})$. We also have the $l$-jet extension

$$j^l_1 H : U \times H^3_1 \rightarrow J^l(U, \mathbb{R})$$
defined by $j^l_1 H(u, v) = j^l h_v(u)$. We consider the trivialisation

$$J^l(U, \mathbb{R}) \equiv U \times \mathbb{R} \times J^l(2, 1),$$

For any submanifold $Q \subset J^l(2, 1)$, we denote $\tilde{Q} = U \times \{0\} \times Q$. Then we have the following proposition as a corollary of Lemma 6 of Wassermann [18].(See also Izumiya et al.[6] and Montaldi [17]).

**Proposition 7.1** Let $Q$ be a submanifold of $J^l(2, 1)$. Then the set

$$T_Q = \{ X \in \text{Embs}(U, H^3_1) | j^l_1 H \text{ is transversal to } \tilde{Q} \}$$
is a residual subset of \( \text{Emb}_S(U, H^3_1) \). If \( Q \) is a closed subset, then \( T_Q \) is open.

On the other hand, let \( F : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow (\mathbb{R}, 0) \) be Morse family and \( \Phi_F \) is the Legendrian immersion with generating family \( F \). By Theorem 6.4, we already have \( \Phi_F \) is Legendrian stable if and only if \( F \) is a \( \mathcal{K} \)-versal deformation of \( f = F|_{\mathbb{R}^k \times \{0\}} \). We need the following characterization of \( \mathcal{K} \)-versality of generating family. Let \( J^l(\mathbb{R}, \mathbb{R}) \) be the \( l \)-jet bundle of \( k \)-variable functions which has the canonical decomposition: \( J^l(\mathbb{R}, \mathbb{R}) \equiv \mathbb{R}^k \times \mathbb{R} \times J^l(k, 1) \). For any Morse family of hypersurfaces \( F \), we define a map germ

\[
j^1F : (\mathbb{R}^k \times \mathbb{R}^n, 0) \rightarrow J^l(\mathbb{R}, \mathbb{R})
\]

by \( j^1F(q, x) = j^1F_x(q) \), where \( F_x(q) = F(q, x) \). We denote \( \mathcal{K}^l(z) \) the \( \mathcal{K} \)-orbit through \( z = j^1(0) \in J^l(k, 1) \). (cf.,[15]). If \( f(q) = F(q, 0) \) is \( l \)-determined relative to \( \mathcal{K} \), then \( F \) is \( \mathcal{K} \)-versal deformation of \( f \) if and only if \( j^1F \) is transversal to \( \mathbb{R}^k \times \{0\} \times \mathcal{K}^l(z) \) (cf.,[15]). Therefore we can apply this characterization to the AdS-height function. By the classification of stable Legendrian singularities of \( n < 6 \) and Proposition 7.1, we have the following theorem.

**Theorem 7.2** There exists an open dense subset \( O \subset \text{Emb}_S(U, H^3_1) \) such that for any \( X \in O \), the germ of the corresponding Legendrian embedding \( L \) at each point is Legendrian stable.

### 8 Classification of singularities of TAdS-Gauss images

In this section we consider the generic singularities of TAdS-Gauss images. By Theorem 7.2 and the classification of function germs [1], We have the following theorem:

**Theorem 8.1** There exists an open dense subset \( O \subset \text{Emb}_S(U, H^3_1) \) such that for any \( X \in O \) the following conditions hold.

(1) The AdS-parabolic set \( K_{\text{AdS}}^{-1}(0) \) is a regular curve. We call such a curve the AdS-parabolic curve.

(2) The TAdS-Gauss image \( T \) along the AdS-parabolic curve is a cuspidal edge except at isolated points. At such the point \( T \) is the swallowtail.

Here, a map germ \( f : (\mathbb{R}^2, a) \rightarrow (\mathbb{R}^3, b) \) is called a cuspidal edge if it is \( \mathcal{A} \)-equivalent to the germ \((u_1, u_2, u_3)\) and a swallowtail if it is \( \mathcal{A} \)-equivalent to the germ \((3u_1^4 + u_1^2u_2, 4u_1^3 + 2u_1u_2, u_2)\).
The assertion of Theorem 8.1 can be interpreted as saying that the Legendrian embedding $L$ of the TAdS-Gauss image $T$ of $X$ is Legendrian stable at each point. Following the terminology of Whitney [19], we say that a spacelike surface $X : U \rightarrow H^3$ has the excellent TAdS-Gauss image $T$ if $L$ is a stable Legendrian immersion germ at each point. In this case, the TAdS-Gauss image $T$ has only cuspidal edges and swallowtails as singularities. Theorem 8.1 assert that a spacelike surface with the excellent TAdS-Gauss image is generic in the space of all spacelike surfaces in $H^3$.

We now consider the geometric meanings of cuspidal edges and swallowtails of the TAdS-Gauss image. We have the following results analogous to the results of Izumiya et al. [6].

**Theorem 8.2**  Let $T : (U, u_0) \rightarrow (H^3, v_0)$ be the excellent TAdS-Gauss image germ of a spacelike surface $X$ and $h_{v_0} : (U, u_0) \rightarrow \mathbb{R}$ be the AdS-height function germ at $v_0 = T(u_0)$. Then we have the following.

1. The point $u_0$ is an AdS-parabolic point of $X$ if and only if AdS-corank $(X, u_0) = 1$.
2. If $u_0$ is an AdS-parabolic point of $X$, then $h_{v_0}$ has the $A_k$-type singularity for $k = 2, 3$.
3. Suppose that $u_0$ is an AdS-parabolic point of $X$. Then the following conditions are equivalent:
   - (a) $T$ has the cuspidal edge at $u_0$;
   - (b) $h_{v_0}$ has the $A_2$-type singularity;
   - (c) AdS-order $(X, u_0) = 2$;
   - (d) the tangent AdS-great-hyperboloidic indicatrix is an ordinary cusp, where a curve $C \subset \mathbb{R}^2$ is called an ordinary cusp if it is diffeomorphic to the curve given by $\{(u_1, u_2)|u_1^2 - u_2^3 = 0\}$.
4. Suppose that $u_0$ is an AdS-parabolic point of $X$. Then the following conditions are equivalent:
   - (a) $T$ has the swallowtail at $u_0$;
   - (b) $h_{v_0}$ has the $A_3$-type singularity;
   - (c) AdS-order $(X, u_0) = 3$;
   - (d) the tangent AdS-great-hyperboloidic indicatrix is an point or a tachnodal, where a curve $C \subset \mathbb{R}^2$ is called a tachnodal if it is diffeomorphic to the curve given by $\{(u_1, u_2)|u_1^2 - u_2^4 = 0\}$.
   - (e) for each $\varepsilon > 0$, there exist two points $u_1, u_2 \in U$ such that $|u_0 - u_i| < \varepsilon$ for $i = 1, 2$, neither of $u_1$ nor $u_2$ is an AdS-parabolic point and the tangent AdS-great-hyperboloids to $M = X(U)$ at $u_1$ and $u_2$ are equal.

**Proof.** By the Proposition 4.1, we have shown that $u_0$ is an AdS-parabolic point if and only if AdS-corank $(X, u_0) \geq 1$. Since $n = 3$, we have AdS-corank $(X, u_0) \leq 2$. Since AdS-height function germ $H : (U \times H^3, (u_0, v_0)) \rightarrow \mathbb{R}$ can be considered as a generating family of the Legendrian embedding germ $L$, $h_{v_0}$ has only the $A_k$-type singularities ($k = 1, 2, 3$). This means that the corank of the Hessian matrix of the $h_{v_0}$ at an AdS-parabolic point is 1. The assertion (2) also follows. For the same reason, the conditions (3) $(a, b, c)$ (respectively, (4) $(a, b, c)$) are equivalent.

On the other hand, if the AdS-height function germ $h_{v_0}$ has the $A_2$-type singularity, it is $K$-equivalent to the germ $\pm u_1^2 + u_2^3$. Since the $K$-equivalence preserves the zero level sets, the tangent AdS-great-hyperboloidic indicatrix is diffeomorphic to the curve given by $\pm u_1^2 + u_2^3 = 0$. This is the ordinary cusp. The normal form for the $A_3$-type singularity is given by $\pm u_1^2 + u_2^4$, so the tangent AdS-great-hyperboloidic indicatrix is diffeomorphic to the curve given by $\pm u_1^2 + u_2^4 = 0$. This means that the condition (3) $(a)$ (respectively, (4) $(d)$) is also equivalent to the other conditions.
For the swallowtail point $u_0$, there is a self-intersection curve approaching $u_0$. On this curve, there are two distinct points $u_1$ and $u_2$ such that $T(u_1) = T(u_2)$. By Lemma 6.2, this means that the tangent AdS-great-hyperboloids to $M = X(U)$ at $u_1$ and $u_2$ are equal. Since there are no other singularities in this case, the condition (4)\{(c)\} characterizes a swallowtail point of $T$. This completes the proof. 

\[\square\]

Figure 2

\begin{figure}[h]
\centering
\begin{subfigure}{0.4\textwidth}
\centering
\includegraphics[width=\textwidth]{ordinary_cusp.png}
\caption{Ordinary cusp}
\end{subfigure}
\hspace{0.5cm}
\begin{subfigure}{0.4\textwidth}
\centering
\includegraphics[width=\textwidth]{tachnodal.png}
\caption{Tachnodal}
\end{subfigure}
\end{figure}

\section{AdS-Monge form}

The notion of the Monge form of a surface in Euclidean 3-space is one of the powerful tools for the study of local properties of the surface from the viewpoint of differential geometry. In this section we consider the analogous notion for a spacelike surface in $H_3^1$.

We now consider a function $f(u_1, u_2)$ with $f(0) = f_u(0) = 0$. Then we have a spacelike surface in $H_3^1$ defined by

\[X_f(u_1, u_2) = (\sqrt{1 + u_1^2 + u_2^2 - f^2(u_1, u_2)}, f(u_1, u_2), u_1, u_2).\]

We can easily calculate $e(0) = (0, 1, 0, 0)$; therefore $T(0) = (0, 1, 0, 0)$. We call $X_f$ a \textit{Anti de Sitter Monge form} (briefly, \textit{AdS-Monge form}). Then we have the following proposition.

\textbf{Proposition 9.1} Any spacelike surface in $H_3^1$ is locally given by the AdS-Monge form.

\textbf{Proof.} Let $X : U \rightarrow H_3^1$ be a spacelike surface. We consider Lorentzian motion of $H_3^1$ which is a transitive action. Therefore, without loss of the generality, we assume that $p = X(0) = (1, 0, 0, 0)$. We denote $M = X(U)$, we have a basis \{\(X(0), e(0), X_u(0), X_{uu}(0)\}\) of $T_p\mathbb{R}^4_2$ such that $T_pM = \{X_u(0), X_{uu}(0)\}_\mathbb{R}$. Applying the Gram-Schmidt procedure we have a pseudo-orthonormal basis \{\(X(0), e(0), e_1, e_2\)\} of $T_p\mathbb{R}^4_2$ such that $T_pM = \{e_1, e_2\}_\mathbb{R}$. In particular, \{\(e_1, e_2\)\} is an orthonormal basis of $T_pM$. Since $p = (1, 0, 0, 0)$, $T_pM$ is considered to be a subspace of $\mathbb{R}^3_0 = \{(0, x_1, x_2, x_3) | x_i \in \mathbb{R}\}$. By a rotation of the space $\mathbb{R}^3_0$, we might assume that $T_pM = \{(0, 0, u_1, u_2) | u_i \in \mathbb{R}\} \subset \mathbb{R}_2^3$. Then the germ $(M, p)$ might be written in the form

\[(f_0(u_1, u_2), f(u_1, u_2), u_1, u_2)\]

with function germs $f_0(u_1, u_2), f(u_1, u_2)$. Since $M \subset H^1_3$, we have the relation

\[f_0(u_1, u_2) = \sqrt{1 + u_1^2 + u_2^2 - f^2(u_1, u_2)}.\]
Since we have $T_p M = \{(0, 0, u_1, u_2) | u_i \in \mathbb{R}\}$, the condition $f(0) = 0$, $f_{u_i}(0) = 0$ are automatically satisfied. □

For the timelike vector $v_0 = (0, 1, 0, 0)$, we consider the AdS-great-hyperboloid $AH(v_0, 0)$. Then we have the AdS-Monge form of $AH(v_0, 0)$:

$$a(u_1, u_2) = (\sqrt{1 + u_1^2 + u_2^2}, 0, u_1, u_2).$$

Here, we can easily check the relation $\langle a(u), v_0 \rangle = 0$.

On the other hand, $a(0) = (1, 0, 0, 0) = p$ and $a_{u_i}(0)$ is equal to the $x_{i+2}$-axis for $i = 1, 2$. This means that $T_p M = T_p(a(u))$. Therefore $a(u) = AH(v_0, 0)$ is the tangent AdS-great-hyperboloid of $M = X_f(U)$ at $p = X_f(0)$. It follows from this fact that the tangent AdS-great-hyperboloidic indicatrix of the AdS-Monge form germ $(X_f, 0)$ is given as follows:

$$X_f^{-1}(AH(v_0, 0)) = \{(u_1, u_2) | f(u_1, u_2) = 0\}.$$

Since the height function of $X_f$ at $v_0$ is

$$h_{v_0}(u) = \langle X_f(u), v_0 \rangle = f(u_1, u_2),$$

we can calculate the Hessian matrix; then we have $\text{Hess}(h_{v_0})(0) = \text{Hess}(f)(0)$. Thus we conclude that $\text{AdS-corank}(X_f, 0) = 2 - \text{rankHess}(f)(0)$.

On the other hand, since $f(0) = f_{u_1}(0) = 0$, we may write

$$f(u_1, u_2) = \frac{1}{2} \bar{k}_1 u_1^2 + \frac{1}{2} \bar{k}_2 u_2^2 + g(u_1, u_2)$$

where $g \in \mathcal{M}_3^3$ and $\bar{k}_1, \bar{k}_2$ are eigenvalues of $(f_{u_1 u_2}(0))$. Under this representation, we can easily calculate $X_{f, u_1 u_2}(0) = (\delta_{ij}, f_{u_1 u_2}(0), 0, 0)$. It follows from this fact that

$$h_{ij}(0) = \langle e(0), X_{f, u_1 u_2}(0) \rangle = f_{u_1 u_2}(0) = \delta_{ij} \bar{k}_i,$$

and

$$g_{ij}(0) = \langle X_{f, u_1}(0), X_{f, u_2}(0) \rangle = \delta_{ij}.$$

Therefore, we have $k_i(0) = \bar{k}_i$ and

$$K_{\text{AdS}}(0) = k_1(0)k_2(0) = \bar{k}_1 \bar{k}_2.$$

The tangent AdS-great-hyperboloidal indicatrix is given by

$$X_f^{-1}(AH(v_0, 0)) = \{(u_1, u_2) | \pm \frac{1}{2} \bar{k}_1 u_1^2 \pm \frac{1}{2} \bar{k}_2 u_2^2 \pm g(u_1, u_2) = 0\} = \{(u_1, u_2) | \pm k_1(0)u_1^2 \pm k_2(0)u_2^2 \pm 2g(u_1, u_2) = 0\}.$$

If we try to draw picture of the TAdS-Gauss image, it might be very hard to give a parameterization. However, by the AdS-Monge form of the tangent AdS-great-hyperboloidal indicatrix germ, we can easy to detect the type of singularities of the TAdS-Gauss image $\mathbb{T}$.

**Example 9.1** Consider the function given by

$$f(u_1, u_2) = 2u_1^2 - 3u_2^2.$$
Then $\bar{k}_1 = 4$, $\bar{k}_2 = 0$. We have $k_1 = 4$, $k_2 = 0$, so that the origin is an AdS-parabolic point. The tangent AdS-great-hyperboloidic indicatrix germ at the origin is the ordinary cusp. By Theorem 8.2, $T(0)$ is the cuspidal edge.

**Example 9.2** Consider the function given by
\[
   f(u_1, u_2) = 2u_1^2 - 4u_2^4.
\]
Then $\bar{k}_1 = 4$, $\bar{k}_2 = 0$. We have $k_1 = 4$, $k_2 = 0$, so that the origin is an AdS-parabolic point. The tangent AdS-great-hyperboloidic indicatrix germ at the origin is the tachnodal. By Theorem 8.2, $T(0)$ is the swallowtail.

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**References**


