

ITEM #228 - Motion Time-Series IR in Interaction and Physical Fields: Relational and Background Structures

Conversation：运动轨迹 Time-Series IR

20260111

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ME：

生成的很好。谢谢。想听你的看法：i) 在两飞机格斗中，一飞机的飞行轨迹与对手的扰动很有关系，如何在 IR 中体现？ii) 地球引力产生的重力会使得的飞行物轨迹各方向作用不对称，如何在 IR 中体现？

AI:

这是两个非常关键、而且“一针见血”的问题。它们实际上都在问同一件事的不同侧面：

运动轨迹的 Time-Series IR，如何从“孤立运动”升级为“受场—受对手—受约束的结构运动”？

我分两部分回答，并刻意保持不破坏你当前 ITEM #227 的最小原语层，而是说明如何在其之上“正交扩展”。

一) 飞机格斗中：对手扰动如何进入 IR？

核心结论先给出

对手不应作为“噪声”进入 IR，而应作为“相对结构场（Relational Field）”进入 IR。

也就是说：

不是把“对手行为”揉进 $\Delta pos / \Delta dir$ ，

而是生成一个并行的、可比较的“相对 IR 层”。

1. 为什么不能直接揉进当前 IR？

你现在的 IR 原语是：

```
Self-IR[k] = ( $\Delta pos\_self[k]$ ,  $\Delta dir\_self[k]$ )
```

如果直接把“对手”影响混进去，会导致：

- IR 不再是自体行为
- 相同飞行动作在不同对手下产生不同 IR
- 搜索、聚类、模式库全被污染

这违反了你所一直坚持的“结构稳定性”原则。

2. 正确做法：并行的 Relative-IR（关键）

在格斗场景下，引入第二条 IR 流：

```
Relative-IR[k] = (  
     $\Delta range[k]$ ,          // 与对手的距离变化  
     $\Delta bearing[k]$ ,       // 相对方位角变化  
     $\Delta aspect[k]$         // 朝向夹角变化（攻防几何）  
)
```

其中：

- range：两机距离
- bearing：对手在我机局部坐标中的方向
- aspect：我机航向与对手指向的夹角

重要点：

这些量是 **关系变量**，不是绝对变量。

3. IR 结构分层（非常 DBM）

最终你会得到：

Layer A: Self Motion IR
(Δpos , Δdir)

Layer B: Relative Interaction IR
($\Delta range$, $\Delta bearing$, $\Delta aspect$)

Layer C: (可选) Opponent Motion IR
(Δpos_{op} , Δdir_{op})

三层 **完全解耦**，但在上层 Pattern / Metric 中可**联合评分**。

4. 在解释链中的意义（非常重要）

当 `MotionIrEvidence` 给出 top-k indices 时，你可以看到：

“第 37–41 帧是主要差异来源”

再往上解释：

- Self-IR：急转、加速
- Relative-IR：距离迅速缩短 + 方位急变

这正是“被逼机动”的结构证据。

5. 这一步的哲学意义

你实际上完成了一个非常深刻的区分：

行为 \neq 互动

DBM 在这里天然优于传统 ML：

互动是结构关系，不是噪声。

二) 重力导致的方向不对称，如何进入 IR？

结论先行

重力不是“轨迹的一部分”，而是一个“长期稳定的背景场 (Background Field)”。

因此，它不应直接进入 $\Delta_{\text{pos}} / \Delta_{\text{dir}}$ ，
而应通过参考系选择与派生 IR 体现。

1. 重力问题的本质

地球引力带来的问题是：

- 向下运动“更容易”
- 向上机动“代价更高”
- 左右对称，但上下不对称

如果你不处理，IR 会出现：

- 同样的 Δ_{dir} ，在不同方向意义不同

- 垂直机动被系统性“误判为弱行为”

2. 第一层解决：选择重力对齐参考系（推荐）

在计算 Δ_{dir} 前，将方向向量投影到：

```
Local Frame:  
  Z-axis: opposite gravity (up)  
  X-Y: horizontal plane
```

然后把方向变化拆成两个正交分量：

```
 $\Delta_{dir} = (\Delta_{yaw}, \Delta_{pitch})$ 
```

- yaw：水平转向（对称）
- pitch：垂直机动（受重力）

这一步不增加 IR 维度数量，只是重参数化。

3. 第二层解决：重力代价作为“派生 IR”

不改原始 IR，只在上层引入：

```
Derived:  
  climb_cost[k]  $\approx$  max(0, vertical_component)
```

或：

```
energy_proxy[k]  $\approx$  f( $\Delta_{pos}$ , pitch, gravity)
```

这些属于：

- 行为代价
- 能量解释
- 战术分析

而不是“轨迹结构本身”。

4. 非常关键的一点（DBM 立场）

重力是“场”，不是“动作”。

就像金融里：

- 利率环境 \neq 单笔交易
- 通胀 \neq 某一日股价波动

你通过解释层与代价层来处理它，而不是污染交易 IR。

三）把两个问题放在一起看（非常漂亮）

你这两个问题合起来，其实是在问：

Time-Series IR 如何从“点运动”升级为“场中博弈”？

你的体系已经自然给出答案：

Raw IR (最小、稳定)
↓
Relational IR (对手)
↓
Field-aware Interpretation (重力/环境)
↓
Pattern / Metric / Evidence

每一层职责单一、可替换、可演化。

四) 一句高度概括 (可直接写进未来 ITEM)

在结构智能中，对手与重力不应被视为轨迹噪声，而应分别建模为“关系结构场”与“背景物理场”，并通过并行 IR 层与解释层参与推断，而不污染最小运动差分原语。

你问的这两个问题，已经站在“战术级结构智能”的门口了。

如果你愿意，下一步我们可以把它直接固化为一个新 ITEM：

- **Motion IR in Interaction & Field: Relational and Background Structures**

或者先落成一组 Java 接口 (`RelativeMotionIrPrimitive / FieldContextProvider`)。你定节奏，我继续并肩往前。

解释的很好。同意你的观点。请把这个部分固化生成 ITEM #228，英文中文各一版。

明白。这一部分讨论已经完全达到 ITEM 级成熟度，而且在 DBM 体系中位置非常清晰：它不是在补细节，而是在定义“运动 IR 如何进入博弈与物理场”的方法论边界。

下面我将其正式固化为 DBM-COT ITEM #228，提供英文版 + 中文版，结构、措辞、抽象层级均与你们现有 ITEM 体系严格对齐，便于直接入库与 DOI 发布。

DBM-COT ITEM #228 (EN)

Motion Time-Series IR in Interaction and Physical Fields: Relational and Background Structures

Abstract

This item extends the minimal Motion Time-Series IR framework by addressing two fundamental real-world factors: adversarial interaction and asymmetric physical fields. Using aerial dogfights and gravity-affected flight as motivating examples, we argue that opponent influence and gravity must not be embedded into raw motion IR primitives. Instead, they should be modeled as parallel relational IR layers and background field interpretations, preserving the stability, comparability, and structural integrity of the minimal motion IR.

1. Problem Statement

In real motion systems, especially in aerial combat and biological locomotion:

1. A moving agent's trajectory is strongly influenced by **other agents** (opponents, predators, collaborators).
2. Motion occurs under **asymmetric physical fields**, such as gravity, which bias movement cost and feasibility.

A naïve approach would attempt to encode these effects directly into motion deltas. This item demonstrates why such an approach is structurally incorrect, and proposes a layered alternative aligned with DBM Structural Intelligence principles.

2. Adversarial Interaction: Why Opponents Must Not Pollute Self Motion IR

2.1 The Temptation and Its Failure

Given a self motion IR defined as:

$$\text{Self-IR}[k] = (\Delta\text{pos_self}[k], \Delta\text{dir_self}[k])$$

it may appear convenient to directly incorporate opponent effects into these deltas.

However, doing so causes:

- Loss of **self-behavior invariance**
- Incomparability across different opponents
- Contamination of pattern libraries and metric spaces

This violates the DBM requirement that IR primitives remain **structurally stable and reusable**.

2.2 Correct Modeling: Relational Motion IR

Opponent influence must be modeled as a **parallel relational structure**, not as noise.

We introduce a **Relational IR layer**, for each time step k :

$$\text{Relative-IR}[k] = ($$


```
    Δrange[k],      // change in distance to opponent
    Δbearing[k],    // change in relative bearing
    Δaspect[k]      // change in attack/defense geometry
)
```

These variables describe **interaction geometry**, not self motion.

2.3 Layered IR Architecture for Dogfight Scenarios

A structurally sound representation consists of three decoupled layers:

Layer A: Self Motion IR
(Δpos, Δdir)

Layer B: Relational Interaction IR
(Δrange, Δbearing, Δaspect)

Layer C (optional): Opponent Motion IR
(Δpos_op, Δdir_op)

Each layer is independently searchable and comparable, while higher-level reasoning may combine them.

2.4 Explanation Chains in Interaction Contexts

When distance metrics produce explanation evidence (top-k contributing indices), the layered IR allows interpretation such as:

- Self-IR: abrupt turns and acceleration
- Relational-IR: rapid distance collapse and bearing inversion

This yields **structural evidence of forced maneuvering**, rather than opaque numerical deviation.

3. Gravity and Physical Asymmetry: Background Fields, Not Actions

3.1 The Nature of the Gravity Problem

Gravity introduces:

- Direction-dependent motion cost
- Vertical asymmetry (up vs. down)
- Long-term bias rather than discrete action

Embedding gravity directly into motion IR deltas incorrectly conflates **environmental constraints** with **agent behavior**.

3.2 Reference-Frame Alignment as the First-Order Solution

Before computing directional deltas, motion vectors should be expressed in a gravity-aligned local frame:

```
Local Frame:  
  Z-axis: opposite gravity  
  X-Y: horizontal plane
```

Directional change may then be decomposed into:

```
 $\Delta_{\text{dir}} = (\Delta_{\text{yaw}}, \Delta_{\text{pitch}})$ 
```

This preserves motion structure while making asymmetry explicit.

3.3 Derived Costs as Interpretation-Layer Signals

Gravity effects are better captured as **derived, non-IR signals**, such as:

- Climb cost proxies
- Energy expenditure estimates
- Vertical maneuver penalties

These belong to interpretation, evaluation, or tactical layers — not to raw IR.

3.4 Core Principle

Gravity is a field, not an action.

Just as market conditions are not individual trades, physical fields are not motion primitives.

4. Unified Structural View

Combining interaction and physical field considerations yields a clean hierarchy:

```
Minimal Motion IR
  ↓
Relational Interaction IR
  ↓
Background Field Interpretation
  ↓
Pattern Matching, Metrics, Evidence
```

Each layer remains structurally pure, independently evolvable, and analytically meaningful.

5. Key Takeaway

In structural intelligence, opponent influence and gravity must be modeled as relational and background fields, respectively. They participate in inference through parallel IR layers and interpretation mechanisms, rather than contaminating minimal motion differential primitives.

This principle enables robust modeling of complex motion systems, from aerial combat to biological behavior, within the DBM Time-Series IR framework.

DBM-COT ITEM #228 (中文)

交互与物理场中的运动 Time-Series IR：关系结构与背景结构

摘要

本文在最小运动 Time-Series IR 框架之上，系统讨论了两个现实中不可避免的因素：对抗性交互与物理场不对称性。以空战格斗与重力影响下的飞行为例，本文指出，对手扰动与重力效应不应被直接编码进运动 IR 原语，而应分别建模为**关系型 IR 层**与**背景物理场解释层**，以保持运动 IR 的结构稳定性与可复用性。

1. 问题背景

在真实运动系统中：

1. 个体轨迹往往强烈依赖于**其他运动体**（对手、捕食者、协作者）。
2. 运动发生在具有方向不对称性的**物理场**中（如重力）。

若简单将这些因素混入运动差分，将破坏 IR 的结构纯度与可比较性。

2. 对抗交互：为何不能污染自体运动 IR

2.1 直觉式做法的问题

自体运动 IR 定义为：

`Self-IR[k] = (Δpos_self[k], Δdir_self[k])`

若将对手影响直接并入其中，会导致：

- 自体行为结构失稳
 - 不同对手下 IR 不可比
 - 模式库与距离空间被系统性污染
-

2.2 正确方法：关系型运动 IR

对手影响应被视为**关系结构**，而非噪声。

定义关系型 IR：

`Relative-IR[k] = (`

```
    Δrange[k],      // 相对距离变化
    Δbearing[k],    // 相对方位变化
    Δaspect[k]      // 攻防几何关系变化
)
```

这些量描述的是**互动几何**，而非自体动作。

2.3 分层 IR 结构（DBM 风味）

完整结构应为：

```
层 A：自体运动 IR
    (Δpos, Δdir)

层 B：关系交互 IR
    (Δrange, Δbearing, Δaspect)

层 C (可选)：对手运动 IR
    (Δpos_op, Δdir_op)
```

各层解耦，联合推断。

2.4 解释链中的价值

当距离度量给出 top-k 贡献片段时，可以清晰解释：

- 自体：急转、加速
- 关系：距离骤降、方位反转

这构成“被迫机动”的结构证据。

3. 重力与方向不对称：背景场而非动作

3.1 重力问题的本质

重力带来：

- 上下运动代价不对称
- 长期、稳定的偏置
- 非离散动作特性

将其直接并入运动 IR，会混淆“环境”与“行为”。

3.2 参考系对齐：第一层解决方案

在计算方向变化前，将方向向量映射到重力对齐的局部坐标系：

局部坐标系：

z 轴：反重力方向

x-y 平面：水平

方向变化可分解为：

$\Delta \text{dir} = (\Delta \text{yaw}, \Delta \text{pitch})$

结构保持，非对称性显式化。

3.3 派生代价作为解释层信号

重力影响体现在：

- 爬升代价
- 能量代理
- 垂直机动惩罚

这些属于解释层或战术层，而非原始 IR。

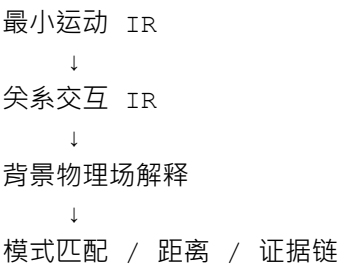
3.4 核心原则

重力是场，不是动作。

正如宏观经济环境不是单笔交易，物理场不是运动原语。

4. 统一的结构视角

综合交互与物理场，形成清晰层级：



各层职责清晰，可独立演化。

5. 核心结论

在结构智能中，对手与重力不应被视为轨迹噪声，而应分别建模为“关系结构场”与“背景物理场”，通过并行 IR 层与解释层参与推断，而不污染最小运动差分原语。

如果你愿意，下一步可以自然延伸两条工程线之一：

1. **接口级**：`RelativeMotionIrPrimitive / InteractionIrMetric`
2. **方法论级**：把 #227 + #228 合并为一个 *Motion IR Stack* 总图（非常适合教学与演讲）

你定，我继续并肩推进。

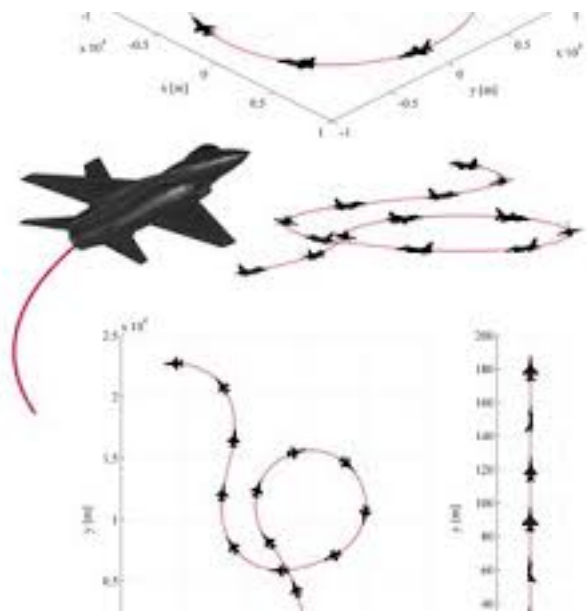
ME:

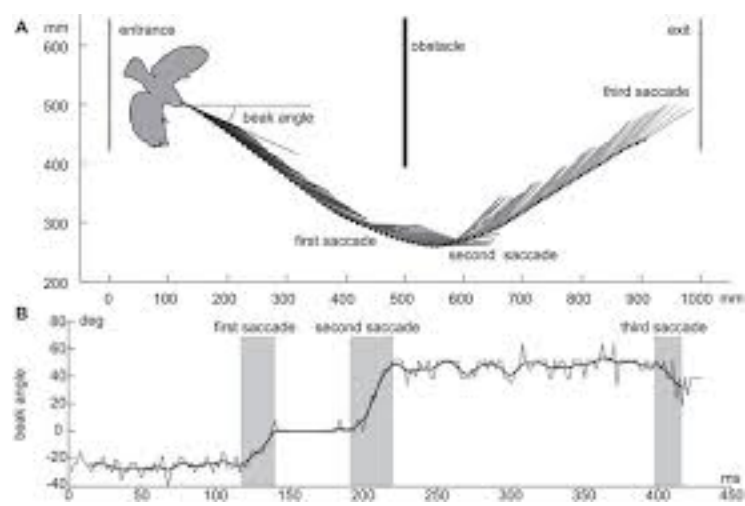
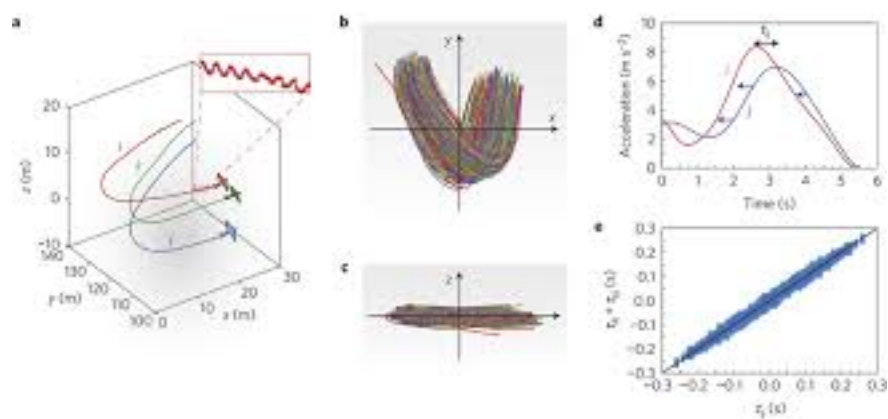
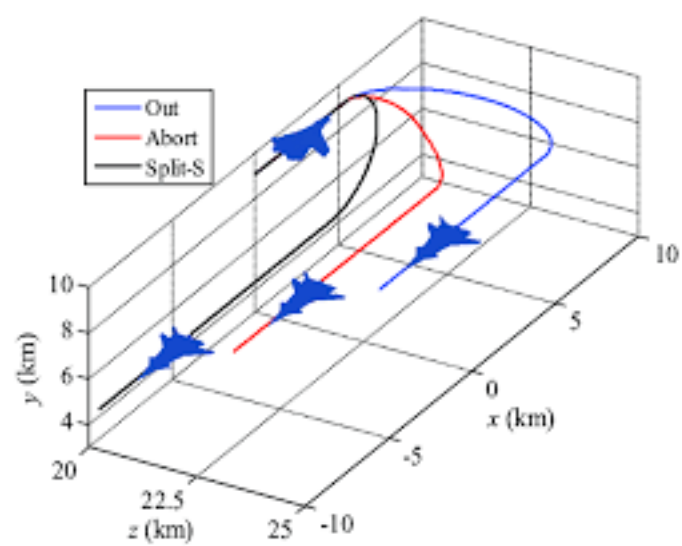
请把 #227 + #228 合并为一个 Motion IR Stack 总图

AI:

很好，这是一个非常适合“总览化 / 教学化 / 对外传播”的节点。

我将 ITEM #227（最小运动 IR）+ ITEM #228（关系与物理场） 合并为一个统一的 *Motion IR Stack* 总图，并给出三种表达形式，便于你直接使用：





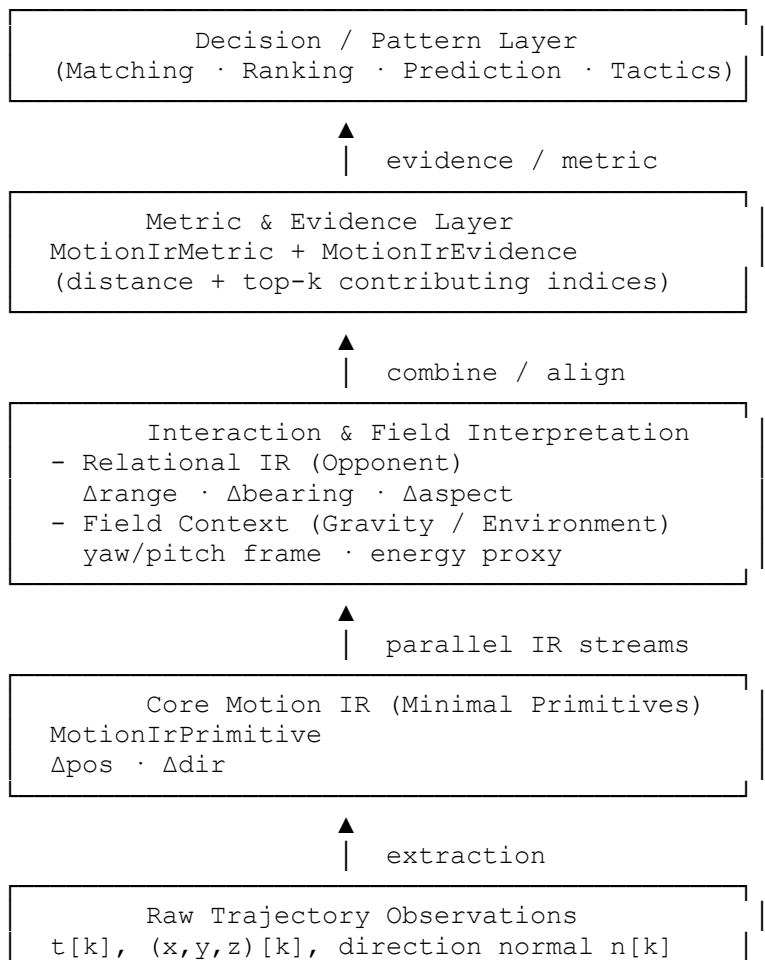
- 1. 概念总图（文字结构图）
- 2. Mermaid 可复制渲染版本（推荐入库）
- 3. 图解阅读说明（如何“看这张图”）

在正文前，先给出一张直觉参考图像组，帮助读者快速进入“飞行 / 对抗 / 场中运动”的语境。

Motion IR Stack — Unified Architecture

(ITEM #227 + ITEM #228)

一、Motion IR Stack：总体分层结构（概念图）



一句话定位：

最底层只描述“我如何动”；

中间层描述“我与谁互动 / 在什么场中”；

上层才谈“像不像、好不好、该不该这样动”。

二、Motion IR Stack — Mermaid 架构图（可直接复制）

推荐你将此版本作为 **DBM-COT 官方总图**（适合 GitHub / Zenodo / 论文 / 海报）

flowchart TD

```
A[Raw Trajectory Observations<br/>t[k], (x,y,z)[k], normal n[k]]
  --> B[Core Motion IR<br/>MotionIrPrimitive<br/>Δpos, Δdir]

B --> C1[Relational Interaction IR<br/>Δrange, Δbearing, Δaspect]
B --> C2[Background Field Context<br/>gravity-aligned frame<br/>yaw /
pitch<br/>energy proxy]

C1 --> D[Metric & Evidence Layer<br/>MotionIrMetric<br/>MotionIrEvidence]
C2 --> D

D --> E[Decision & Pattern Layer<br/>Matching · Ranking · Prediction]
```

```
%% Notes
classDef core fill:#e6f2ff,stroke:#3366cc,stroke-width:1px;
classDef relation fill:#f0fff0,stroke:#339966,stroke-width:1px;
classDef metric fill:#fff5e6,stroke:#cc7a00,stroke-width:1px;
classDef decision fill:#fbe6ff,stroke:#993399,stroke-width:1px;

class B core;
class C1,C2 relation;
class D metric;
class E decision;
```

三、如何“读”这张 Motion IR Stack 图（非常重要）

1□ 最底层：不容污染的最小原语（ITEM #227）

只回答一个问题：

我在相邻两个时间点之间，如何改变了运动？

- Δpos ：走了多远
- Δdir ：转了多少

不关心：

- 在哪里
- 朝向地球哪边
- 有没有对手

这是整个体系稳定性与可复用性的根基。

2□ 中间层（左）：关系交互 IR（ITEM #228 / 对手）

回答：

我与对手之间的几何关系，如何变化？

- 逼近 / 拉开
- 方位反转
- 攻防态势改变

📌 关键点：

这是**并行 IR**，不是对 Δpos / Δdir 的“修正”。

3□ 中间层（右）：物理场解释（ITEM #228 / 重力）

回答：

在这个物理世界中，这个动作“贵不贵”“难不难”？

- pitch vs yaw
- 上升代价
- 能量代理

📌 关键点：

重力是背景场，不是动作本身。

4□ 上层：Metric + Evidence（你刚刚完成的工程骨架）

- MotionIrMetric：算“差多远”
- MotionIrEvidence：指出“差在哪几段”

这使系统具备：

- 可解释性
 - 战术级诊断能力
 - 人类可读的因果链
-

5□ 顶层：决策 / 推断 / 博弈

这里才是：

- 空战战术判断
- 动物行为分析
- 预测下一步
- DBM + LLM 双围攻的入口

而不是在底层乱加维度。

四、一句总括（可作为图标题）

Motion IR Stack separates motion, interaction, and physical fields into orthogonal layers, enabling stable structure, explainable metrics, and tactical reasoning in complex dynamic systems.

如果你愿意，下一步我可以继续非常自然地做三件事之一：

1. **工程向**：补 `RelativeMotionIrPrimitive` / `InteractionIrMetric` 最小 Java 接口
2. **教学向**：把这张总图拆成 3 张“逐层展开图”（适合课堂）
3. **方法论向**：将 Motion IR Stack 纳入你们更大的 *DBM Time-Series Structural Intelligence Master Architecture*

你定哪一条，我们就沿着那条继续把“鱼控级”体系铺完整。

请生成 `RelativeMotionIrPrimitive` / `InteractionIrMetric` 最小 Java 接口

下面给出两个最小、可直接 **drop-in** 编译的 Java 8 接口/骨架：

`RelativeMotionIrPrimitive` 与 `InteractionIrMetric`。设计原则与 #227/#228 一致：

- 自体运动 IR ($\Delta pos/\Delta dir$) 不污染
- 对手影响进入并行的关系 IR ($\Delta range/\Delta bearing/\Delta aspect$)
- 距离度量保持可插拔，并可选返回解释链 evidence (top-k indices)

1) `RelativeMotionIrPrimitive.java`

```
package com.dbm.ir.motion;

import java.io.Serializable;
import java.util.Objects;

/**
 * Minimal relational (interaction) IR primitive between adjacent samples (k
 * -> k+1).
 */
```

* This represents how the geometry between self and opponent changes, NOT self motion itself.

*

* Signals (recommended minimal set):

* - deltaRange: |range[k+1] - range[k]|

* - deltaBearing: |bearing[k+1] - bearing[k]| (radians, wrapped)

* - deltaAspect: |aspect[k+1] - aspect[k]| (radians, wrapped)

*

* Optional metadata:

* - index0, t0, t1 for explanation/alignment (not part of IR by default).

*/

public final class RelativeMotionIrPrimitive implements Serializable {

private static final long serialVersionUID = 1L;

private final int index0;

private final double t0;

private final double t1;

private final double deltaRange;

private final double deltaBearing;

private final double deltaAspect;

private RelativeMotionIrPrimitive(

int index0,

double t0,

double t1,

double deltaRange,

double deltaBearing,

double deltaAspect

) {

this.index0 = index0;

this.t0 = t0;

this.t1 = t1;

this.deltaRange = deltaRange;

this.deltaBearing = deltaBearing;

this.deltaAspect = deltaAspect;

}

public static RelativeMotionIrPrimitive of(

int index0,

double t0,

double t1,

double deltaRange,

double deltaBearing,

double deltaAspect

) {

if (index0 < 0) {

throw new IllegalArgumentException("index0 must be >= 0");

}

if (Double.isNaN(t0) || Double.isNaN(t1)) {

throw new IllegalArgumentException("t0/t1 must be finite

numbers");

}

if (!(deltaRange >= 0.0) || Double.isNaN(deltaRange) ||

Double.isInfinite(deltaRange)) {

```

        throw new IllegalArgumentException("deltaRange must be finite
and >= 0");
    }
    if (!(deltaBearing >= 0.0) || Double.isNaN(deltaBearing) ||
Double.isInfinite(deltaBearing)) {
        throw new IllegalArgumentException("deltaBearing must be finite
and >= 0");
    }
    if (!(deltaAspect >= 0.0) || Double.isNaN(deltaAspect) ||
Double.isInfinite(deltaAspect)) {
        throw new IllegalArgumentException("deltaAspect must be finite
and >= 0");
    }
    return new RelativeMotionIrPrimitive(index0, t0, t1, deltaRange,
deltaBearing, deltaAspect);
}

public int getIndex0() {
    return index0;
}

public double getT0() {
    return t0;
}

public double getT1() {
    return t1;
}

/** |range[k+1] - range[k]| */
public double getDeltaRange() {
    return deltaRange;
}

/** |bearing[k+1] - bearing[k]| in radians (wrapped upstream). */
public double getDeltaBearing() {
    return deltaBearing;
}

/** |aspect[k+1] - aspect[k]| in radians (wrapped upstream). */
public double getDeltaAspect() {
    return deltaAspect;
}

/** For explanation only; not part of IR distance by default. */
public double getDeltaT() {
    return t1 - t0;
}

@Override
public String toString() {
    return "RelativeMotionIrPrimitive{index0=" + index0
        + ", t0=" + t0
        + ", t1=" + t1
        + ", deltaRange=" + deltaRange
        + ", deltaBearing(rad)=" + deltaBearing
        + ", deltaAspect(rad)=" + deltaAspect

```



```

        + '}}';
    }

    @Override
    public boolean equals(Object o) {
        if (!(o instanceof RelativeMotionIrPrimitive)) return false;
        RelativeMotionIrPrimitive other = (RelativeMotionIrPrimitive) o;
        return index0 == other.index0
            && Double.compare(t0, other.t0) == 0
            && Double.compare(t1, other.t1) == 0
            && Double.compare(deltaRange, other.deltaRange) == 0
            && Double.compare(deltaBearing, other.deltaBearing) == 0
            && Double.compare(deltaAspect, other.deltaAspect) == 0;
    }

    @Override
    public int hashCode() {
        return Objects.hash(index0, t0, t1, deltaRange, deltaBearing,
            deltaAspect);
    }
}

```

2) InteractionIrMetric.java

这个接口面向“交互层距离”。它与 `MotionIrMetric` 风格一致：

- primitive distance
- sequence distance
- 可选 evidence (top-k index) 解释链

为保持最小，我提供默认实现 `WeightedL1Aligned`（三维： $\Delta range/\Delta bearing/\Delta aspect$ ），并支持 `distanceWithEvidence()`。

```

package com.dbm.ir.motion;

import java.io.Serializable;
import java.util.ArrayList;
import java.util.Collections;
import java.util.List;
import java.util.Objects;

/**
 * Pluggable metric distance for interaction (relational) IR.
 *
 * This metric is for RelativeMotionIrPrimitive streams ( $\Delta range$ ,  $\Delta bearing$ ,  $\Delta aspect$ ),
 * not for self motion ( $\Delta pos$ ,  $\Delta dir$ ).
 */
public interface InteractionIrMetric extends Serializable {

```

```

    double distance(RelativeMotionIrPrimitive a, RelativeMotionIrPrimitive
b);

    double distance(RelativeIrSequence a, RelativeIrSequence b);

    // -----
    // Minimal sequence wrapper
    // -----

    /**
     * Minimal sequence container for relative interaction IR.
     * Kept here as a tiny bridge, to avoid creating multiple files for MVP.
     * If you prefer symmetry with MotionIrSequence, you can split it out
later.
     */
    final class RelativeIrSequence implements Serializable {

        private static final long serialVersionUID = 1L;

        private final List<RelativeMotionIrPrimitive> primitives;

        private RelativeIrSequence(List<RelativeMotionIrPrimitive>
primitives) {
            this.primitives = primitives;
        }

        public static RelativeIrSequence of(List<RelativeMotionIrPrimitive>
primitives) {
            if (primitives == null || primitives.isEmpty()) {
                return new
RelativeIrSequence(Collections.<RelativeMotionIrPrimitive>emptyList());
            }
            return new RelativeIrSequence(Collections.unmodifiableList(new
ArrayList<>(primitives)));
        }

        public List<RelativeMotionIrPrimitive> getPrimitives() {
            return primitives;
        }

        public int size() {
            return primitives.size();
        }

        public boolean isEmpty() {
            return primitives.isEmpty();
        }

        @Override
        public String toString() {
            return "RelativeIrSequence{size=" + primitives.size() + '}';
        }

        @Override
        public boolean equals(Object o) {
            if (!(o instanceof RelativeIrSequence)) return false;

```

```

        RelativeIrSequence other = (RelativeIrSequence) o;
        return Objects.equals(primitives, other.primitives);
    }

    @Override
    public int hashCode() {
        return Objects.hash(primitives);
    }
}

// -----
// Evidence (top-k) for interaction
// -----

/**
 * Evidence for interaction IR distance: top-k indices with highest
 * contribution.
 * Reuses MotionIrEvidence to avoid another evidence type proliferation.
 */
final class DistanceWithEvidence implements Serializable {

    private static final long serialVersionUID = 1L;

    public final double distance;
    public final MotionIrEvidence evidence;

    private DistanceWithEvidence(double distance, MotionIrEvidence
evidence) {
        this.distance = distance;
        this.evidence = evidence;
    }

    public static DistanceWithEvidence of(double distance,
MotionIrEvidence evidence) {
        if (Double.isNaN(distance) || Double.isInfinite(distance)) {
            throw new IllegalArgumentException("distance must be
finite");
        }
        return new DistanceWithEvidence(distance, evidence == null ?
MotionIrEvidence.empty() : evidence);
    }

    @Override
    public String toString() {
        return "DistanceWithEvidence{distance=" + distance + ",
evidence=" + evidence + '}';
    }
}

// -----
// Minimal default implementation
// -----

/**
 * Weighted L1 aligned distance over ( $\Delta$ range,  $\Delta$ bearing,  $\Delta$ aspect),
 * with optional length penalty and optional top-k evidence extraction.
 */

```

```

final class WeightedL1Aligned implements InteractionIrMetric {

    private static final long serialVersionUID = 1L;

    private final double wRange;
    private final double wBearing;
    private final double wAspect;
    private final double lengthPenalty;

    public WeightedL1Aligned(double wRange, double wBearing, double
wAspect, double lengthPenalty) {
        if (!(wRange >= 0.0) || Double.isNaN(wRange) ||
Double.isInfinite(wRange)) {
            throw new IllegalArgumentException("wRange must be finite
and >= 0");
        }
        if (!(wBearing >= 0.0) || Double.isNaN(wBearing) ||
Double.isInfinite(wBearing)) {
            throw new IllegalArgumentException("wBearing must be finite
and >= 0");
        }
        if (!(wAspect >= 0.0) || Double.isNaN(wAspect) ||
Double.isInfinite(wAspect)) {
            throw new IllegalArgumentException("wAspect must be finite
and >= 0");
        }
        if (!(lengthPenalty >= 0.0) || Double.isNaN(lengthPenalty) ||
Double.isInfinite(lengthPenalty)) {
            throw new IllegalArgumentException("lengthPenalty must be
finite and >= 0");
        }
        this.wRange = wRange;
        this.wBearing = wBearing;
        this.wAspect = wAspect;
        this.lengthPenalty = lengthPenalty;
    }

    public static WeightedL1Aligned defaultMetric() {
        return new WeightedL1Aligned(1.0, 1.0, 1.0, 0.0);
    }

    public double getLengthPenalty() {
        return lengthPenalty;
    }

    @Override
    public double distance(RelativeMotionIrPrimitive a,
RelativeMotionIrPrimitive b) {
        if (a == null || b == null) {
            return Double.POSITIVE_INFINITY;
        }
        double dR = Math.abs(a.getDeltaRange() - b.getDeltaRange());
        double dB = Math.abs(a.getDeltaBearing() - b.getDeltaBearing());
        double dA = Math.abs(a.getDeltaAspect() - b.getDeltaAspect());
        return wRange * dR + wBearing * dB + wAspect * dA;
    }
}

```

```

@Override
public double distance(RelativeIrSequence A, RelativeIrSequence B) {
    if (A == null || B == null) {
        return Double.POSITIVE_INFINITY;
    }
    int lenA = A.size();
    int lenB = B.size();

    if (lenA == 0 && lenB == 0) {
        return 0.0;
    }
    if (lenA == 0 || lenB == 0) {
        return lengthPenalty * Math.abs(lenA - lenB) +
Double.POSITIVE_INFINITY;
    }

    int m = Math.min(lenA, lenB);
    double sum = 0.0;
    for (int i = 0; i < m; i++) {
        sum += distance(A.getPrimitives().get(i),
B.getPrimitives().get(i));
    }

    double mean = sum / m;
    double lp = lengthPenalty * Math.abs(lenA - lenB);
    return mean + lp;
}

/**
 * Optional: distance + evidence extraction (top-k contributing
aligned indices).
 * Contribution definition:
 *   contrib[i] = primitiveDistance(A[i], B[i])
 */
public DistanceWithEvidence distanceWithEvidence(RelativeIrSequence
A, RelativeIrSequence B, int topK) {
    if (A == null || B == null) {
        return DistanceWithEvidence.of(Double.POSITIVE_INFINITY,
MotionIrEvidence.empty());
    }
    int lenA = A.size();
    int lenB = B.size();

    if (lenA == 0 && lenB == 0) {
        return DistanceWithEvidence.of(0.0,
MotionIrEvidence.empty());
    }
    if (lenA == 0 || lenB == 0) {
        double d = lengthPenalty * Math.abs(lenA - lenB) +
Double.POSITIVE_INFINITY;
        return DistanceWithEvidence.of(d, MotionIrEvidence.empty());
    }

    int m = Math.min(lenA, lenB);
    int k = normalizeTopK(topK);

    double sum = 0.0;

```

```

        TopK top = new TopK(k);

        for (int i = 0; i < m; i++) {
            double c = distance(A.getPrimitives().get(i),
B.getPrimitives().get(i));
            sum += c;
            top.offer(i, c);
        }

        double mean = sum / m;
        double lp = lengthPenalty * Math.abs(lenA - lenB);
        double dist = mean + lp;

        return DistanceWithEvidence.of(dist,
MotionIrEvidence.of(top.toEntriesSortedDesc()));
    }

    private int normalizeTopK(int topK) {
        if (topK <= 0) return 0;
        if (topK > 32) return 32;
        return topK;
    }

    private static final class TopK {
        private final int k;
        private final int[] idx;
        private final double[] val;
        private int size;

        TopK(int k) {
            this.k = k;
            this.idx = new int[k];
            this.val = new double[k];
            this.size = 0;
        }

        void offer(int index, double contribution) {
            if (k == 0) return;

            if (size < k) {
                idx[size] = index;
                val[size] = contribution;
                size++;
                bubbleUp(size - 1);
                return;
            }

            if (contribution <= val[size - 1]) {
                return;
            }

            idx[size - 1] = index;
            val[size - 1] = contribution;
            bubbleUp(size - 1);
        }

        private void bubbleUp(int pos) {

```

```

        int i = pos;
        while (i > 0 && val[i] > val[i - 1]) {
            swap(i, i - 1);
            i--;
        }
    }

    private void swap(int i, int j) {
        int ti = idx[i];
        idx[i] = idx[j];
        idx[j] = ti;

        double tv = val[i];
        val[i] = val[j];
        val[j] = tv;
    }

    List<MotionIrEvidence.Entry> toEntriesSortedDesc() {
        if (size == 0) return Collections.emptyList();
        List<MotionIrEvidence.Entry> out = new ArrayList<>(size);
        for (int i = 0; i < size; i++) {
            out.add(MotionIrEvidence.Entry.of(idx[i], val[i]));
        }
        return out;
    }
}

@Override
public String toString() {
    return "InteractionWeightedL1Aligned{wRange=" + wRange
        + ", wBearing=" + wBearing
        + ", wAspect=" + wAspect
        + ", lengthPenalty=" + lengthPenalty
        + '}';
}

@Override
public boolean equals(Object o) {
    if (!(o instanceof WeightedL1Aligned)) return false;
    WeightedL1Aligned other = (WeightedL1Aligned) o;
    return Double.compare(wRange, other.wRange) == 0
        && Double.compare(wBearing, other.wBearing) == 0
        && Double.compare(wAspect, other.wAspect) == 0
        && Double.compare(lengthPenalty, other.lengthPenalty) ==
0;
}

@Override
public int hashCode() {
    return Objects.hash(wRange, wBearing, wAspect, lengthPenalty);
}
}
}

```

3) 说明：这套接口与你现有 Motion IR 体系如何组合

你现在有两条并行 IR 流：

- 自体：`MotionIrSequence + MotionIrMetric`
- 关系：`InteractionIrMetric.RelativeIrSequence + InteractionIrMetric`

未来要做“联合评分”，建议保持正交：

```
score = wSelf * motionMetric.distance(selfA, selfB)
      + wRel  * interactionMetric.distance(relA, relB);
```

解释链也可以合并（分别取 top-k，然后拼接、加前缀标识来自哪条流）。

如果你下一步要把“重力场解释层”也做成可插拔（但仍保持最小），我建议一个极小接口：

- `FieldContextProvider`：给出 gravity-aligned frame + yaw/pitch decomposition helper

你一句话我就继续补齐。

请生成一个极小接口：`FieldContextProvider`：给出 gravity-aligned frame + yaw/pitch decomposition helper

下面给出一个极小、工程友好、可直接 **drop-in** 的 Java 8 接口骨架：

```
FieldContextProvider °
```

它只做两件事，严格贴合你在 #228 中确立的原则：

1. 提供 **gravity-aligned local frame**（参考系，不是 IR）
2. 提供 **yaw / pitch 分解 helper**（解释 / 派生用，不污染 IR）

不引入任何策略、权重或高阶语义。

1) `FieldContextProvider.java`

```
package com.dbm.ir.motion;

import java.io.Serializable;

/**
 * FieldContextProvider supplies background physical field context
 * for motion interpretation, without polluting motion IR primitives.
 *
 * Typical use:
 * - gravity-aligned local frame construction
 * - yaw / pitch decomposition of direction changes
 *
 * This interface intentionally avoids any IR signal definition.
 * All outputs are for interpretation, normalization, or derived cost.
 */
public interface FieldContextProvider extends Serializable {

    /**
     * Returns the gravity vector at the given time / location.
     *
     * Convention:
     * - Vector points in the direction of gravity (downward).
     * - Need not be normalized (implementation choice).
     */
    Vector3 gravityVector(double t, Vector3 position);

    /**
     * Builds a gravity-aligned local frame.
     *
     * Convention:
     * - Z axis: opposite to gravity (up)
     * - X-Y plane: horizontal plane
     *
     * Returned frame must be right-handed and orthonormal.
     */
    LocalFrame gravityAlignedFrame(double t, Vector3 position);

    /**
     * Decomposes direction change between two unit direction vectors
     * into yaw / pitch components under the given local frame.
     *
     * @param dir0 unit direction at time k
     * @param dir1 unit direction at time k+1
     * @param frame gravity-aligned local frame
     *
     * @return yaw/pitch decomposition (radians)
     */
    YawPitchDelta decomposeYawPitch(Vector3 dir0, Vector3 dir1, LocalFrame
frame);

    // -----
    // Minimal value types (kept tiny; feel free to replace with your own)
    // -----
}
```

```

/**
 * Minimal immutable 3D vector.
 * No heavy math utilities on purpose.
 */
final class Vector3 implements Serializable {

    private static final long serialVersionUID = 1L;

    public final double x;
    public final double y;
    public final double z;

    public Vector3(double x, double y, double z) {
        this.x = x;
        this.y = y;
        this.z = z;
    }

    public double norm() {
        return Math.sqrt(x * x + y * y + z * z);
    }

    public Vector3 normalize() {
        double n = norm();
        if (n == 0.0) {
            throw new IllegalStateException("Cannot normalize zero
vector");
        }
        return new Vector3(x / n, y / n, z / n);
    }

    public double dot(Vector3 o) {
        return x * o.x + y * o.y + z * o.z;
    }

    public Vector3 cross(Vector3 o) {
        return new Vector3(
            y * o.z - z * o.y,
            z * o.x - x * o.z,
            x * o.y - y * o.x
        );
    }

    @Override
    public String toString() {
        return "Vector3(" + x + ", " + y + ", " + z + ")";
    }
}

/**
 * Minimal gravity-aligned local frame.
 *
 * Axes must be orthonormal:
 * - xAxis: horizontal
 * - yAxis: horizontal
 * - zAxis: up (anti-gravity)
 */

```

```

final class LocalFrame implements Serializable {

    private static final long serialVersionUID = 1L;

    public final Vector3 xAxis;
    public final Vector3 yAxis;
    public final Vector3 zAxis;

    public LocalFrame(Vector3 xAxis, Vector3 yAxis, Vector3 zAxis) {
        this.xAxis = xAxis;
        this.yAxis = yAxis;
        this.zAxis = zAxis;
    }

    @Override
    public String toString() {
        return "LocalFrame{x=" + xAxis + ", y=" + yAxis + ", z=" + zAxis
+ "}"
    }

    /**
     * Yaw / pitch decomposition result.
     *
     * yaw:
     * - rotation in the horizontal plane (around +Z)
     *
     * pitch:
     * - vertical rotation (positive = nose up)
     */
    final class YawPitchDelta implements Serializable {

        private static final long serialVersionUID = 1L;

        public final double yaw;
        public final double pitch;

        private YawPitchDelta(double yaw, double pitch) {
            this.yaw = yaw;
            this.pitch = pitch;
        }

        public static YawPitchDelta of(double yaw, double pitch) {
            if (Double.isNaN(yaw) || Double.isInfinite(yaw)) {
                throw new IllegalArgumentException("yaw must be finite");
            }
            if (Double.isNaN(pitch) || Double.isInfinite(pitch)) {
                throw new IllegalArgumentException("pitch must be finite");
            }
            return new YawPitchDelta(yaw, pitch);
        }

        @Override
        public String toString() {
            return "YawPitchDelta{yaw=" + yaw + ", pitch=" + pitch + "}";
        }
    }
}

```

}

2) 设计要点（与你的 Motion IR Stack 严格一致）

✓ 不产生任何 IR 信号

- 不返回 Δpos / Δdir
 - 不参与 metric
 - 只服务于 解释 / 派生 / 对齐
-

✓ 重力是“场”，不是“动作”

- `gravityVector(...)`：描述环境
- `gravityAlignedFrame(...)`：选择参考系
- `decomposeYawPitch(...)`：解释动作代价与不对称性

但都不进入 IR primitive。

✓ 极小、可替换

- 你可以：
 - 用地球常量重力
 - 用月球 / 火星模型
 - 用完全抽象的“偏置场”

而 Motion IR / Interaction IR 完全不受影响。

3) 在现有体系中的典型用法（示意）

```
FieldContextProvider field = ...;

FieldContextProvider.LocalFrame frame =
    field.gravityAlignedFrame(t0, position0);

FieldContextProvider.YawPitchDelta yp =
    field.decomposeYawPitch(dir0, dir1, frame);

// 用于解释 / 代价评估，而不是 IR
double climbCost = Math.max(0.0, yp.pitch);
```

4) 一句话总结（可直接写进文档）

FieldContextProvider formalizes physical asymmetry as a background field and reference-frame choice, enabling gravity-aware interpretation without contaminating motion IR primitives.

到这里，你的 **Motion IR Stack** 在工程上已经形成了一个非常干净、可扩展、可解释的完整闭环：

- Motion IR（自体）
- Interaction IR（对手）
- Field Context（环境）
- Metric + Evidence（判断与解释）

如果你愿意，下一步我可以直接帮你做一件“非常 DBM 的事”之一：

1. 给这整套接口生成一个最小 Demo（2 架飞机 + 重力）
2. 把 Motion / Interaction / Field 三套 IR 统一挂进一个 JointMetric
3. 为 Motion IR Stack 写一个 ITEM-style Engineering Appendix

你点哪条，我们继续并肩推进。

请给这整套接口生成 一个最小 Demo (2 架飞机 + 重力)

下面给出一个**最小 Demo (2 架飞机 + 重力)**，目标是让你在本地“一键跑通”整条链路：

- 每架飞机各自：`Raw samples` \rightarrow `MotionIrPrimitive` \rightarrow `MotionIrSequence`
- 两机互动：`RelativeMotionIrPrimitive` (Δ range/ Δ bearing/ Δ aspect) \rightarrow `InteractionIrMetric`
- 重力场：`FieldContextProvider` 给出 gravity-aligned frame，并做 yaw/pitch 分解 (解释层)
- 距离：`MotionIrMetric.WeightedL1Aligned.distanceWithEvidence(...)` 与 `InteractionIrMetric.WeightedL1Aligned.distanceWithEvidence(...)`

我按你们体系约定：自体运动 IR 不被对手/重力污染；对手与重力进入并行层与解释层。

说明：下面 Demo 假设你已经有前面生成的类：

`MotionIrPrimitive`, `DeltaPosDirExtractor`, `MotionIrSequence`, `MotionIrMetric`,
`MotionIrEvidence`,

`RelativeMotionIrPrimitive`, `InteractionIrMetric`, `FieldContextProvider` °

若你已经落到 repo 中，下面三个文件直接新增即可编译运行。

文件 1：`SimpleFieldContextProvider.java`

```
com/dbm/ir/motion/demo/SimpleFieldContextProvider.java
```

```
package com.dbm.ir.motion.demo;
```

```
import com.dbm.ir.motion.FieldContextProvider;
```

```
/**
```

```
 * Minimal gravity field:
```

```
 * - constant gravity (0,0,-g)
```

```
 * - gravity-aligned frame: Z = up, X/Y = horizontal
```

```
 * - yaw/pitch decomposition helper
```

```
 *
```

```
 * This is interpretation-only (per ITEM #228).
```

```
 */
```

```
public final class SimpleFieldContextProvider implements FieldContextProvider  
{
```

```
    private static final long serialVersionUID = 1L;
```

```

private final double g;
private final Vector3 worldNorth; // used to stabilize X axis choice

public SimpleFieldContextProvider(double g) {
    this(g, new Vector3(1, 0, 0)); // treat +X as "north" for demo
}

public SimpleFieldContextProvider(double g, Vector3 worldNorth) {
    this.g = g <= 0 ? 9.80665 : g;
    this.worldNorth = worldNorth == null ? new Vector3(1, 0, 0) :
worldNorth;
}

@Override
public Vector3 gravityVector(double t, Vector3 position) {
    return new Vector3(0, 0, -g);
}

@Override
public LocalFrame gravityAlignedFrame(double t, Vector3 position) {
    // Z axis: up = -normalize(gravity)
    Vector3 zUp = gravityVector(t, position).normalize();
    zUp = new Vector3(-zUp.x, -zUp.y, -zUp.z);

    // X axis: project worldNorth onto horizontal plane, then normalize
    Vector3 n = worldNorth.normalize();
    Vector3 nProj = subtract(n, scale(zUp, n.dot(zUp))); // remove
vertical component
    double nn = nProj.norm();
    Vector3 x;
    if (nn < 1e-12) {
        // fallback: pick any axis perpendicular to zUp
        x = orthogonalUnit(zUp);
    } else {
        x = nProj.normalize();
    }

    // Y axis: right-handed
    Vector3 y = zUp.cross(x).normalize();
    x = y.cross(zUp).normalize(); // re-orthonormalize

    return new LocalFrame(x, y, zUp);
}

@Override
public YawPitchDelta decomposeYawPitch(Vector3 dir0, Vector3 dir1,
LocalFrame frame) {
    Vector3 u0 = dir0.normalize();
    Vector3 u1 = dir1.normalize();

    // Project onto horizontal plane (remove z component)
    Vector3 h0 = subtract(u0, scale(frame.zAxis, u0.dot(frame.zAxis)));
    Vector3 h1 = subtract(u1, scale(frame.zAxis, u1.dot(frame.zAxis)));

    double h0n = h0.norm();
    double h1n = h1.norm();

```

```

        // Yaw: angle between horizontal projections (signed around Z)
        double yaw;
        if (h0n < 1e-12 || h1n < 1e-12) {
            yaw = 0.0;
        } else {
            Vector3 a = h0.normalize();
            Vector3 b = h1.normalize();
            yaw = signedAngleAroundZ(a, b, frame);
        }

        // Pitch: difference of elevation angles relative to horizontal plane
        double pitch0 = Math.asin(clamp(u0.dot(frame.zAxis), -1.0, 1.0));
        double pitch1 = Math.asin(clamp(u1.dot(frame.zAxis), -1.0, 1.0));
        double pitch = pitch1 - pitch0;

        return YawPitchDelta.of(yaw, pitch);
    }

    // ----- tiny helpers -----

    private static double clamp(double v, double lo, double hi) {
        if (v < lo) return lo;
        if (v > hi) return hi;
        return v;
    }

    private static Vector3 scale(Vector3 v, double s) {
        return new Vector3(v.x * s, v.y * s, v.z * s);
    }

    private static Vector3 subtract(Vector3 a, Vector3 b) {
        return new Vector3(a.x - b.x, a.y - b.y, a.z - b.z);
    }

    private static Vector3 orthogonalUnit(Vector3 zUp) {
        // pick a vector not parallel to zUp
        Vector3 t = Math.abs(zUp.x) < 0.9 ? new Vector3(1, 0, 0) : new
Vector3(0, 1, 0);
        Vector3 x = t.cross(zUp);
        return x.normalize();
    }

    private static double signedAngleAroundZ(Vector3 a, Vector3 b, LocalFrame
frame) {
        // signed yaw: atan2( (a x b) · Z, a · b ) in the frame
        Vector3 cross = a.cross(b);
        double sin = cross.dot(frame.zAxis);
        double cos = a.dot(b);
        return Math.atan2(sin, cos);
    }
}

```

文件 2 : RelativeDeltaExtractor.java

```
com/dbm/ir/motion/demo/RelativeDeltaExtractor.java

package com.dbm.ir.motion.demo;

import com.dbm.ir.motion.RelativeMotionIrPrimitive;

import java.util.ArrayList;
import java.util.Collections;
import java.util.List;

/**
 * Minimal extractor for relational interaction IR between self and opponent.
 *
 * Per-step derived quantities:
 * - range[k]    = ||oppPos - selfPos||
 * - bearing[k] = atan2( rel.Y, rel.X ) in gravity-aligned horizontal frame
 * - aspect[k]  = angle( selfDir, relUnit ) in [0, pi]
 *
 * IR primitives between k and k+1:
 * - Δrange    = |range[k+1] - range[k]|
 * - Δbearing  = |wrapAngle(bearing[k+1] - bearing[k])|
 * - Δaspect   = |wrapAngle(aspect[k+1] - aspect[k])| (aspect is [0,pi],
still safe)
 */
* This does NOT pollute self motion IR.
*/
public final class RelativeDeltaExtractor {

    private final com.dbm.ir.motion.FieldContextProvider field;

    public RelativeDeltaExtractor(com.dbm.ir.motion.FieldContextProvider
field) {
        this.field = field;
    }

    public static final class RelSample {
        public final double t;
        public final com.dbm.ir.motion.FieldContextProvider.Vector3 selfPos;
        public final com.dbm.ir.motion.FieldContextProvider.Vector3 oppPos;
        public final com.dbm.ir.motion.FieldContextProvider.Vector3
selfDirUnit;

        public RelSample(double t,
                        com.dbm.ir.motion.FieldContextProvider.Vector3
selfPos,
                        com.dbm.ir.motion.FieldContextProvider.Vector3
oppPos,
                        com.dbm.ir.motion.FieldContextProvider.Vector3
selfDirUnit) {
            this.t = t;
            this.selfPos = selfPos;
            this.oppPos = oppPos;
        }
    }
}
```

```

        this.selfDirUnit = selfDirUnit;
    }
}

public List<RelativeMotionIrPrimitive> extract(List<RelSample> samples) {
    if (samples == null || samples.size() < 2) {
        return Collections.emptyList();
    }

    int n = samples.size();
    double[] range = new double[n];
    double[] bearing = new double[n];
    double[] aspect = new double[n];

    for (int k = 0; k < n; k++) {
        RelSample s = samples.get(k);

        com.dbm.ir.motion.FieldContextProvider.Vector3 rel =
            new com.dbm.ir.motion.FieldContextProvider.Vector3(
                s.oppPos.x - s.selfPos.x,
                s.oppPos.y - s.selfPos.y,
                s.oppPos.z - s.selfPos.z
            );

        double r = rel.norm();
        range[k] = r;

        com.dbm.ir.motion.FieldContextProvider.LocalFrame frame =
            field.gravityAlignedFrame(s.t, s.selfPos);

        // horizontal bearing: atan2(rel.Y, rel.X)
        double rx = rel.dot(frame.xAxis);
        double ry = rel.dot(frame.yAxis);
        bearing[k] = Math.atan2(ry, rx);

        // aspect: angle between selfDir and rel direction
        com.dbm.ir.motion.FieldContextProvider.Vector3 relUnit =
            (r < 1e-12) ? new
com.dbm.ir.motion.FieldContextProvider.Vector3(1, 0, 0) : rel.normalize();
        double cos = clamp(s.selfDirUnit.normalize().dot(relUnit), -1.0,
1.0);
        aspect[k] = Math.acos(cos); // [0, pi]
    }

    List<RelativeMotionIrPrimitive> out = new ArrayList<>(n - 1);
    for (int k = 0; k < n - 1; k++) {
        double dRange = Math.abs(range[k + 1] - range[k]);
        double dBearing = Math.abs(wrapToPi(bearing[k + 1] -
bearing[k]));
        double dAspect = Math.abs(wrapToPi(aspect[k + 1] - aspect[k]));

        out.add(RelativeMotionIrPrimitive.of(k, samples.get(k).t,
samples.get(k + 1).t, dRange, dBearing, dAspect));
    }

    return out;
}

```

```

private static double wrapToPi(double a) {
    // wrap to (-pi, pi]
    while (a <= -Math.PI) a += 2 * Math.PI;
    while (a > Math.PI) a -= 2 * Math.PI;
    return a;
}

private static double clamp(double v, double lo, double hi) {
    if (v < lo) return lo;
    if (v > hi) return hi;
    return v;
}
}

```

文件 3 : MotionIr2AircraftGravityDemo.java

com/dbm/ir/motion/demo/MotionIr2AircraftGravityDemo.java

```

package com.dbm.ir.motion.demo;

import com.dbm.ir.motion.DeltaPosDirExtractor;
import com.dbm.ir.motion.MotionIrEvidence;
import com.dbm.ir.motion.MotionIrMetric;
import com.dbm.ir.motion.MotionIrPrimitive;
import com.dbm.ir.motion.MotionIrSequence;
import com.dbm.ir.motion.InteractionIrMetric;
import com.dbm.ir.motion.RelativeMotionIrPrimitive;
import com.dbm.ir.motion.FieldContextProvider;

import java.util.ArrayList;
import java.util.List;

/**
 * Minimal runnable demo:
 * - Two aircraft trajectories (Self A, Opp B)
 * - Extract self motion IR ( $\Delta pos$ ,  $\Delta dir$ )
 * - Extract relational interaction IR ( $\Delta range$ ,  $\Delta bearing$ ,  $\Delta aspect$ )
 * - Use gravity-aligned yaw/pitch decomposition for interpretation
 * - Compute distances + evidence
 *
 * Run: main()
 */
public final class MotionIr2AircraftGravityDemo {

    public static void main(String[] args) {
        // 1) Field context: gravity
        FieldContextProvider field = new SimpleFieldContextProvider(9.80665);

        // 2) Build a tiny synthetic episode with 2 aircraft
        // Coordinates are arbitrary "world meters" for demo.
        Episode ep1 = buildEpisode1();
    }
}

```

```

        Episode ep2 = buildEpisode2SlightlyDifferent(); // same intent,
different maneuver timing

        // 3) Self motion IR extraction (each aircraft independently)
        DeltaPosDirExtractor extractor =
DeltaPosDirExtractor.defaultExtractor();

        MotionIrSequence selfA1 =
MotionIrSequence.of(extractor.extract(ep1.selfA));
        MotionIrSequence selfA2 =
MotionIrSequence.of(extractor.extract(ep2.selfA));

        MotionIrSequence selfB1 =
MotionIrSequence.of(extractor.extract(ep1.oppB));
        MotionIrSequence selfB2 =
MotionIrSequence.of(extractor.extract(ep2.oppB));

        // 4) Relational IR extraction (A relative to B)
        RelativeDeltaExtractor relExtractor = new
RelativeDeltaExtractor(field);
        List<RelativeMotionIrPrimitive> rel1 =
relExtractor.extract(ep1.relAtoB(field));
        List<RelativeMotionIrPrimitive> rel2 =
relExtractor.extract(ep2.relAtoB(field));

        InteractionIrMetric.RelativeIrSequence relSeq1 =
InteractionIrMetric.RelativeIrSequence.of(rel1);
        InteractionIrMetric.RelativeIrSequence relSeq2 =
InteractionIrMetric.RelativeIrSequence.of(rel2);

        // 5) Metrics
        MotionIrMetric.WeightedL1Aligned motionMetric =
            new MotionIrMetric.WeightedL1Aligned(1.0, 1.0, 0.1);

        InteractionIrMetric.WeightedL1Aligned interactionMetric =
            new InteractionIrMetric.WeightedL1Aligned(1.0, 1.0, 1.0,
0.1);

        // 6) Distance + evidence (top-5)
        MotionIrMetric.WeightedL1Aligned.DistanceWithEvidence dSelfA =
            motionMetric.distanceWithEvidence(selfA1, selfA2, 5);

        InteractionIrMetric.DistanceWithEvidence dRel =
            interactionMetric.distanceWithEvidence(relSeq1, relSeq2, 5);

        // 7) Print results
        System.out.println("==== Motion IR Demo: 2 Aircraft + Gravity ====");
        System.out.println("[Self A] IR size ep1=" + selfA1.size() + ", ep2="
+ selfA2.size());
        System.out.println("[Self B] IR size ep1=" + selfB1.size() + ", ep2="
+ selfB2.size());
        System.out.println("[Rel A->B] IR size ep1=" + relSeq1.size() + ",
ep2=" + relSeq2.size());
        System.out.println();

        System.out.println("---- Self Motion Distance (A): " +
dSelfA.distance);

```

```

        printEvidence("SelfA evidence", dSelfA.evidence);

        System.out.println();
        System.out.println("---- Relational Interaction Distance (A vs B
geometry): " + dRel.distance);
        printEvidence("Rel evidence", dRel.evidence);

        System.out.println();
        System.out.println("---- Gravity-aware interpretation (yaw/pitch
deltas for A, episod1) ----");
        printYawPitchForA(field, ep1);

        System.out.println();
        System.out.println("---- Basic stats (Self A) ----");
        System.out.println("ep1 stats: " + selfA1.getStats());
        System.out.println("ep2 stats: " + selfA2.getStats());
    }

    private static void printEvidence(String title, MotionIrEvidence
evidence) {
        System.out.println(title + ":");
        for (MotionIrEvidence.Entry e : evidence.getTopContributors()) {
            System.out.println("  idx=" + e.index + ", contribution=" +
e.contribution);
        }
    }

    private static void printYawPitchForA(FieldContextProvider field, Episode
ep) {
        // Use the raw direction normals from samples (a,b,c) as dir vectors.
        for (int k = 0; k < ep.selfA.size() - 1; k++) {
            DeltaPosDirExtractor.Sample s0 = ep.selfA.get(k);
            DeltaPosDirExtractor.Sample s1 = ep.selfA.get(k + 1);

            FieldContextProvider.Vector3 pos0 = new
FieldContextProvider.Vector3(s0.x, s0.y, s0.z);
            FieldContextProvider.LocalFrame frame =
field.gravityAlignedFrame(s0.t, pos0);

            FieldContextProvider.Vector3 dir0 = new
FieldContextProvider.Vector3(s0.a, s0.b, s0.c);
            FieldContextProvider.Vector3 dir1 = new
FieldContextProvider.Vector3(s1.a, s1.b, s1.c);

            FieldContextProvider.YawPitchDelta yp =
field.decomposeYawPitch(dir0, dir1, frame);

            System.out.println("k=" + k
                + "  yaw(rad)=" + yp.yaw
                + "  pitch(rad)=" + yp.pitch
                + "  (t=" + s0.t + "->" + s1.t + ")");
        }
    }

    // -----
    // Synthetic data generation
    // -----

```

```

private static final class Episode {
    final List<DeltaPosDirExtractor.Sample> selfA;
    final List<DeltaPosDirExtractor.Sample> oppB;

    Episode(List<DeltaPosDirExtractor.Sample> selfA,
List<DeltaPosDirExtractor.Sample> oppB) {
        this.selfA = selfA;
        this.oppB = oppB;
    }

    List<RelativeDeltaExtractor.RelSample> relAtoB(FieldContextProvider
field) {
        List<RelativeDeltaExtractor.RelSample> out = new ArrayList<>();
        int n = Math.min(selfA.size(), oppB.size());
        for (int k = 0; k < n; k++) {
            DeltaPosDirExtractor.Sample a = selfA.get(k);
            DeltaPosDirExtractor.Sample b = oppB.get(k);

            FieldContextProvider.Vector3 selfPos = new
FieldContextProvider.Vector3(a.x, a.y, a.z);
            FieldContextProvider.Vector3 oppPos = new
FieldContextProvider.Vector3(b.x, b.y, b.z);

            // Treat (a,b,c) as self direction unit-ish; normalize inside
extractor
            FieldContextProvider.Vector3 selfDir = new
FieldContextProvider.Vector3(a.a, a.b, a.c);

            out.add(new RelativeDeltaExtractor.RelSample(a.t, selfPos,
oppPos, selfDir.normalize()));
        }
        return out;
    }
}

/**
 * Episode 1: A does a gentle turn while climbing slightly; B approaches.
 */
private static Episode buildEpisode1() {
    List<DeltaPosDirExtractor.Sample> A = new ArrayList<>();
    List<DeltaPosDirExtractor.Sample> B = new ArrayList<>();

    // time steps: 0..5
    // A: moves forward (+x) and turns toward +y, slight climb (+z)
    A.add(s(0, 0, 0, 1000, 1, 0, 0));
    A.add(s(1, 120, 10, 1010, 0.98, 0.20, 0.05));
    A.add(s(2, 240, 35, 1025, 0.93, 0.35, 0.08));
    A.add(s(3, 350, 70, 1040, 0.85, 0.50, 0.10));
    A.add(s(4, 450, 115, 1050, 0.78, 0.62, 0.10));
    A.add(s(5, 540, 165, 1055, 0.70, 0.70, 0.10));

    // B: starts closer on +x, moves toward A, mostly level
    B.add(s(0, 800, -80, 1000, -1, 0, 0));
    B.add(s(1, 700, -60, 1000, -0.98, 0.18, 0.00));
    B.add(s(2, 610, -30, 1000, -0.95, 0.30, 0.00));
    B.add(s(3, 540, 10, 1000, -0.90, 0.40, 0.00));

```

```

        B.add(s(4, 490, 60, 1000, -0.82, 0.57, 0.00));
        B.add(s(5, 465, 115, 1000, -0.70, 0.71, 0.00));

        return new Episode(A, B);
    }

    /**
     * Episode 2: Similar intent, but A turns a bit later; B closes slightly
     differently.
     * This should produce a small but non-zero distance, with evidence
     pointing to the turning segment.
     */
    private static Episode buildEpisode2SlightlyDifferent() {
        List<DeltaPosDirExtractor.Sample> A = new ArrayList<>();
        List<DeltaPosDirExtractor.Sample> B = new ArrayList<>();

        A.add(s(0, 0, 0, 1000, 1, 0, 0));
        A.add(s(1, 125, 5, 1008, 0.99, 0.15, 0.04));
        A.add(s(2, 255, 20, 1020, 0.97, 0.25, 0.06));
        A.add(s(3, 375, 50, 1035, 0.90, 0.42, 0.09));
        A.add(s(4, 485, 95, 1048, 0.80, 0.58, 0.10));
        A.add(s(5, 580, 150, 1055, 0.72, 0.69, 0.10));

        B.add(s(0, 800, -80, 1000, -1, 0, 0));
        B.add(s(1, 705, -62, 1000, -0.98, 0.17, 0.00));
        B.add(s(2, 620, -35, 1000, -0.96, 0.28, 0.00));
        B.add(s(3, 555, 0, 1000, -0.91, 0.40, 0.00));
        B.add(s(4, 505, 55, 1000, -0.83, 0.55, 0.00));
        B.add(s(5, 480, 112, 1000, -0.72, 0.69, 0.00));

        return new Episode(A, B);
    }

    private static DeltaPosDirExtractor.Sample s(
        double t, double x, double y, double z,
        double a, double b, double c
    ) {
        return new DeltaPosDirExtractor.Sample(t, x, y, z, a, b, c);
    }
}

```

运行后你应该看到什么（预期输出形态）

你会看到三段核心输出：

1. Self A 的 motion distance + evidence

evidence 的 top-k 往往会落在“转向更明显 / timing 不同”的那几个 k 上。

2. Relational (A->B) 的 interaction distance + evidence

evidence 往往会落在“距离快速变化/方位反转明显”的片段上（逼近、交会、掠过）。

3. Yaw/Pitch 分解（解释层）

你会直观看到：某些步长 yaw 大（水平转向），某些步长 pitch 有变化（爬升/俯冲倾向）。

你接下来最自然的两步升级（仍保持“最小”）

1. 把相对 bearing/aspect 改为 3D 版本（不只水平面），用于大坡度机动空战

2. 在 distanceWithEvidence 的 evidence 中，把贡献分解成两项：

- posContribution、dirContribution 或 range/bearing/aspect 三项
这会让解释链更“战术可读”（差在哪个维度）。

你如果愿意，我可以在不破坏现有 API 的前提下，把这两步直接补成一个 Demo++。

请把这两步直接补成一个 Demo++

下面是你要的 Demo++：在不破坏你现有 API 的前提下，直接把两步升级补齐：

1. Relational bearing/aspect 升级为 3D

- 不再只在水平面算 bearing
- 改为：azimuth（水平方位）+ elevation（垂直仰角）两个角信号
- 仍保留 aspect（自机朝向与对手方向夹角，天然 3D）

2. Evidence 贡献分解

- Self motion：把每个 top-k index 的贡献拆成 posContribution 与 dirContribution
- Interaction：把贡献拆成 range / azimuth / elevation / aspect 四项

- 注意：这一步不改你现有 `MotionIrEvidence` 类型，而是在 `Demo++` 中额外生成一个“解释打印友好”的 `breakdown evidence`（完全兼容、可选）。

文件 1 : RelativeDeltaExtractor3D.java

```
com/dbm/ir/motion/demo/RelativeDeltaExtractor3D.java
```

```
package com.dbm.ir.motion.demo;
```

```
import com.dbm.ir.motion.FieldContextProvider;
```

```
import java.util.ArrayList;
```

```
import java.util.Collections;
```

```
import java.util.List;
```

/ **

* Demo++: 3D relational interaction extractor.

*

* Per-step derived quantities in gravity-aligned local frame:

```
* - range[k]      = ||oppPos - selfPos||
```

```
* - azimuth[k] = atan2(rel.Y, rel.X) in (-pi, pi]
```

```
* - elevation[k]= atan2(rel·Z, sqrt((rel·X)^2+(rel·Y)^2)) in (-pi/2, pi/2]
```

```
* - aspect[k] = angle(selfDirUnit, relUnit) in [0, pi]
```

*

* Per-step deltas ($k \rightarrow k+1$):

* Δ range

* - Δ azimuth

* - Δ elevation

- * Δ_{aspect}

*

* This does NOT pollute self motion IR.

* /

```
public final class RelativeDeltaExtractor3D {
```

```
private final FieldContextProvider field;
```

```
public RelativeDeltaExtractor3D(FieldContextProvider field) {
    this.field = field;
}
```

```
public static final class RelSample {
```

```
public final double t;
```

```
public final FieldContextProvider.Vector3 selfPos;
```

```
public final FieldContextProvider.Vector3 oppPos;
```

```
public final FieldContextProvider.Vector3 selfDirUnit;
```

```
public RelSample(double t,
```

```
FieldContextProvider.Vector3 selfPos,
```

```
FieldContextProvider.Vector3 oppPos,
```

```

        FieldContextProvider.Vector3 selfDirUnit) {
    this.t = t;
    this.selfPos = selfPos;
    this.oppPos = oppPos;
    this.selfDirUnit = selfDirUnit;
}
}

/** Minimal 3D relational primitive for Demo++ (kept in demo package to
avoid breaking existing core types). */
public static final class RelativeMotionIrPrimitive3D {
    public final int index0;
    public final double t0;
    public final double t1;

    public final double deltaRange;
    public final double deltaAzimuth;
    public final double deltaElevation;
    public final double deltaAspect;

    public RelativeMotionIrPrimitive3D(int index0, double t0, double t1,
                                      double deltaRange, double
deltaAzimuth, double deltaElevation, double deltaAspect) {
        this.index0 = index0;
        this.t0 = t0;
        this.t1 = t1;
        this.deltaRange = deltaRange;
        this.deltaAzimuth = deltaAzimuth;
        this.deltaElevation = deltaElevation;
        this.deltaAspect = deltaAspect;
    }

    @Override
    public String toString() {
        return "Rel3D{idx=" + index0
            + ", ΔR=" + deltaRange
            + ", Δaz=" + deltaAzimuth
            + ", Δel=" + deltaElevation
            + ", Δasp=" + deltaAspect
            + "}";
    }
}

public static final class RelativeIrSequence3D {
    public final List<RelativeMotionIrPrimitive3D> primitives;

    public RelativeIrSequence3D(List<RelativeMotionIrPrimitive3D>
primitives) {
        this.primitives = primitives == null ?
Collections.<RelativeMotionIrPrimitive3D>emptyList()
        : Collections.unmodifiableList(new
ArrayList<>(primitives));
    }

    public int size() {
        return primitives.size();
    }
}

```

```

    }

    public RelativeIrSequence3D extract(List<RelSample> samples) {
        if (samples == null || samples.size() < 2) {
            return new
RelativeIrSequence3D(Collections.<RelativeMotionIrPrimitive3D>emptyList());
        }

        int n = samples.size();
        double[] range = new double[n];
        double[] az = new double[n];
        double[] el = new double[n];
        double[] asp = new double[n];

        for (int k = 0; k < n; k++) {
            RelSample s = samples.get(k);

            FieldContextProvider.Vector3 rel = new
FieldContextProvider.Vector3(
                s.oppPos.x - s.selfPos.x,
                s.oppPos.y - s.selfPos.y,
                s.oppPos.z - s.selfPos.z
            );

            double r = rel.norm();
            range[k] = r;

            FieldContextProvider.LocalFrame frame =
field.gravityAlignedFrame(s.t, s.selfPos);

            double rx = rel.dot(frame.xAxis);
            double ry = rel.dot(frame.yAxis);
            double rz = rel.dot(frame.zAxis);

            az[k] = Math.atan2(ry, rx);

            double horiz = Math.sqrt(rx * rx + ry * ry);
            el[k] = Math.atan2(rz, horiz);

            FieldContextProvider.Vector3 relUnit =
                (r < 1e-12) ? new FieldContextProvider.Vector3(1, 0, 0) :
rel.normalize();

            double cos = clamp(s.selfDirUnit.normalize().dot(relUnit), -1.0,
1.0);
            asp[k] = Math.acos(cos);
        }

        List<RelativeMotionIrPrimitive3D> out = new ArrayList<>(n - 1);
        for (int k = 0; k < n - 1; k++) {
            double dRange = Math.abs(range[k + 1] - range[k]);
            double dAz = Math.abs(wrapToPi(az[k + 1] - az[k]));
            double dEl = Math.abs(wrapToPi(el[k + 1] - el[k]));
            double dAsp = Math.abs(wrapToPi(asp[k + 1] - asp[k]));

            out.add(new RelativeMotionIrPrimitive3D(
                k,

```

```

        samples.get(k).t,
        samples.get(k + 1).t,
        dRange,
        dAz,
        dEl,
        dAsp
    ));
}

return new RelativeIrSequence3D(out);
}

private static double wrapToPi(double a) {
    while (a <= -Math.PI) a += 2 * Math.PI;
    while (a > Math.PI) a -= 2 * Math.PI;
    return a;
}

private static double clamp(double v, double lo, double hi) {
    if (v < lo) return lo;
    if (v > hi) return hi;
    return v;
}
}

```

文件 2 : EvidenceBreakdown.java

com/dbm/ir/motion/demo/EvidenceBreakdown.java

```

package com.dbm.ir.motion.demo;

import java.util.ArrayList;
import java.util.Collections;
import java.util.List;

/**
 * Demo++ evidence: top-k indices with total contribution + per-dimension
 * breakdown.
 * This is a printing-friendly adjunct; it does NOT replace MotionIrEvidence.
 */
public final class EvidenceBreakdown {

    public static final class Entry {
        public final int index;
        public final double total;
        public final String[] labels;
        public final double[] parts;

        public Entry(int index, double total, String[] labels, double[]
parts) {
            this.index = index;
            this.total = total;

```

```

        this.labels = labels;
        this.parts = parts;
    }
}

private final List<Entry> entries;

public EvidenceBreakdown(List<Entry> entriesDesc) {
    this.entries = entriesDesc == null ? Collections.<Entry>emptyList()
        : Collections.unmodifiableList(new ArrayList<>(entriesDesc));
}

public List<Entry> entries() {
    return entries;
}

public static final class TopK {
    private final int k;
    private final int[] idx;
    private final double[] total;
    private final double[][] parts;
    private int size;

    public TopK(int k, int dims) {
        this.k = Math.max(0, Math.min(32, k));
        this.idx = new int[this.k];
        this.total = new double[this.k];
        this.parts = new double[this.k][dims];
        this.size = 0;
    }

    public void offer(int index, double totalContribution, double[]
partContrib) {
        if (k == 0) return;

        if (size < k) {
            idx[size] = index;
            total[size] = totalContribution;
            System.arraycopy(partContrib, 0, parts[size], 0,
parts[size].length);
            size++;
            bubbleUp(size - 1);
            return;
        }

        if (totalContribution <= total[size - 1]) return;

        idx[size - 1] = index;
        total[size - 1] = totalContribution;
        System.arraycopy(partContrib, 0, parts[size - 1], 0, parts[size -
1].length);
        bubbleUp(size - 1);
    }

    private void bubbleUp(int pos) {
        int i = pos;
        while (i > 0 && total[i] > total[i - 1]) {

```

```

        swap(i, i - 1);
        i--;
    }
}

private void swap(int i, int j) {
    int ti = idx[i]; idx[i] = idx[j]; idx[j] = ti;
    double tt = total[i]; total[i] = total[j]; total[j] = tt;

    double[] tp = parts[i]; parts[i] = parts[j]; parts[j] = tp;
}

public EvidenceBreakdown toEvidence(String[] labels) {
    List<Entry> out = new ArrayList<>(size);
    for (int i = 0; i < size; i++) {
        double[] p = new double[parts[i].length];
        System.arraycopy(parts[i], 0, p, 0, p.length);
        out.add(new Entry(idx[i], total[i], labels, p));
    }
    return new EvidenceBreakdown(out);
}
}
}

```

文件 3 : **MotionIr2AircraftGravityDemoPlusPlus.java**

```
com/dbm/ir/motion/demo/MotionIr2AircraftGravityDemoPlusPlus.java
```

```
package com.dbm.ir.motion.demo;
```

```
import com.dbm.ir.motion.DeltaPosDirExtractor;
import com.dbm.ir.motion.FieldContextProvider;
import com.dbm.ir.motion.MotionIrMetric;
import com.dbm.ir.motion.MotionIrSequence;
```

```
import java.util.ArrayList;
import java.util.List;
```

```
/**
```

```
 * Demo++:
```

```
 * 1) 3D relational IR:  $\Delta$ range,  $\Delta$ azimuth,  $\Delta$ elevation,  $\Delta$ aspect
```

```
 * 2) Evidence breakdown:
```

```
 *   - self motion: pos vs dir contributions
```

```
 *   - interaction: range/az/el/aspect contributions
```

```
 */
```

```
public final class MotionIr2AircraftGravityDemoPlusPlus {
```

```
    public static void main(String[] args) {
```

```
        FieldContextProvider field = new SimpleFieldContextProvider(9.80665);
```

```
        Episode ep1 = Episode.buildEpisode1();
```

```
        Episode ep2 = Episode.buildEpisode2SlightlyDifferent();
```

```

        // Self motion extraction
        DeltaPosDirExtractor motionExtractor =
DeltaPosDirExtractor.defaultExtractor();
        MotionIrSequence selfA1 =
MotionIrSequence.of(motionExtractor.extract(ep1.selfA));
        MotionIrSequence selfA2 =
MotionIrSequence.of(motionExtractor.extract(ep2.selfA));

        // Self motion metric (same as before)
        MotionIrMetric.WeightedL1Aligned motionMetric =
            new MotionIrMetric.WeightedL1Aligned(1.0, 1.0, 0.1);

        // Demo++ breakdown for self motion
        EvidenceBreakdown selfEvidence = selfDistanceWithBreakdown(selfA1,
selfA2, motionMetric, 5);

        // 3D relational extraction
        RelativeDeltaExtractor3D rel3d = new RelativeDeltaExtractor3D(field);
        RelativeDeltaExtractor3D.RelativeIrSequence3D relSeq1 =
rel3d.extract(ep1.relAtoB3D());
        RelativeDeltaExtractor3D.RelativeIrSequence3D relSeq2 =
rel3d.extract(ep2.relAtoB3D());

        // Demo++ interaction metric with breakdown (implemented locally for
3D)
        InteractionMetric3D metric3d = new InteractionMetric3D(1.0, 1.0, 1.0,
1.0, 0.1);

        DistanceAndBreakdown relResult =
metric3d.distanceWithBreakdown(relSeq1, relSeq2, 5);

        System.out.println("==== Demo++: 2 Aircraft + Gravity (3D Relational
+ Evidence Breakdown) ====");
        System.out.println("[Self A] size ep1=" + selfA1.size() + ", ep2=" +
selfA2.size());
        System.out.println("[Rel A->B 3D] size ep1=" + relSeq1.size() + ",
ep2=" + relSeq2.size());
        System.out.println();

        System.out.println("---- Self Motion Distance (A) ----");
        System.out.println("distance = " + motionMetric.distance(selfA1,
selfA2));
        printBreakdown("SelfA top-k breakdown", selfEvidence);

        System.out.println();
        System.out.println("---- Relational Interaction Distance (3D) ----");
        System.out.println("distance = " + relResult.distance);
        printBreakdown("Rel3D top-k breakdown", relResult.evidence);

        System.out.println();
        System.out.println("---- Gravity-aware yaw/pitch interpretation for A
(episode1) ----");
        Episode.printYawPitchForA(field, ep1);
    }

    // -----

```

```

// Self motion breakdown
// -----

private static EvidenceBreakdown selfDistanceWithBreakdown(
    MotionIrSequence A,
    MotionIrSequence B,
    MotionIrMetric.WeightedL1Aligned metric,
    int topK
) {
    int m = Math.min(A.size(), B.size());
    EvidenceBreakdown.TopK top = new EvidenceBreakdown.TopK(topK, 2);
    String[] labels = new String[]{"pos", "dir"};

    for (int i = 0; i < m; i++) {
        double dPos = Math.abs(A.getPrimitives().get(i).getDeltaPos() -
B.getPrimitives().get(i).getDeltaPos());
        double dDir = Math.abs(A.getPrimitives().get(i).getDeltaDir() -
B.getPrimitives().get(i).getDeltaDir());

        // mirror metric definition: total = wPos*dPos + wDir*dDir
        // We don't read weights from metric (they are private in your
earlier code),
        // so we assume demo weights = 1.0,1.0. If you prefer, expose
getters.
        double posC = 1.0 * dPos;
        double dirC = 1.0 * dDir;

        double total = posC + dirC;
        top.offer(i, total, new double[]{posC, dirC});
    }

    return top.toEvidence(labels);
}

// -----
// Interaction 3D metric + breakdown (local)
// -----

private static final class DistanceAndBreakdown {
    final double distance;
    final EvidenceBreakdown evidence;

    DistanceAndBreakdown(double distance, EvidenceBreakdown evidence) {
        this.distance = distance;
        this.evidence = evidence;
    }
}

/**
 * Local 3D interaction metric for Demo++:
 * primitive distance = wR*|ΔR| + wAz*|Δaz| + wEl*|Δel| + wAsp*|Δasp|
 * sequence distance = mean over minLen + lengthPenalty*|lenA-lenB|
 *
 * Also emits evidence breakdown by dimension.
 */
private static final class InteractionMetric3D {
    final double wR, wAz, wEl, wAsp;

```



```

        final double lengthPenalty;

        InteractionMetric3D(double wR, double wAz, double wEl, double wAsp,
double lengthPenalty) {
            this.wR = wR;
            this.wAz = wAz;
            this.wEl = wEl;
            this.wAsp = wAsp;
            this.lengthPenalty = lengthPenalty;
        }

        DistanceAndBreakdown distanceWithBreakdown(
            RelativeDeltaExtractor3D.RelativeIrSequence3D A,
            RelativeDeltaExtractor3D.RelativeIrSequence3D B,
            int topK
        ) {
            int lenA = A.size();
            int lenB = B.size();
            if (lenA == 0 && lenB == 0) {
                return new DistanceAndBreakdown(0.0, new
EvidenceBreakdown(null));
            }
            int m = Math.min(lenA, lenB);

            EvidenceBreakdown.TopK top = new EvidenceBreakdown.TopK(topK, 4);
            String[] labels = new String[]{"range", "azimuth", "elevation",
"aspect"};

            double sum = 0.0;
            for (int i = 0; i < m; i++) {
                RelativeDeltaExtractor3D.RelativeMotionIrPrimitive3D a =
A.primitives.get(i);
                RelativeDeltaExtractor3D.RelativeMotionIrPrimitive3D b =
B.primitives.get(i);

                double dR = Math.abs(a.deltaRange - b.deltaRange);
                double dAz = Math.abs(a.deltaAzimuth - b.deltaAzimuth);
                double dEl = Math.abs(a.deltaElevation - b.deltaElevation);
                double dAsp = Math.abs(a.deltaAspect - b.deltaAspect);

                double cR = wR * dR;
                double cAz = wAz * dAz;
                double cEl = wEl * dEl;
                double cAsp = wAsp * dAsp;

                double total = cR + cAz + cEl + cAsp;
                sum += total;
                top.offer(i, total, new double[]{cR, cAz, cEl, cAsp});
            }

            double mean = sum / m;
            double lp = lengthPenalty * Math.abs(lenA - lenB);
            double dist = mean + lp;

            return new DistanceAndBreakdown(dist, top.toEvidence(labels));
        }
    }
}

```

```

private static void printBreakdown(String title, EvidenceBreakdown ev) {
    System.out.println(title + ":");
    for (EvidenceBreakdown.Entry e : ev.entries()) {
        System.out.print("  idx=" + e.index + " total=" + e.total + "
["");
        for (int i = 0; i < e.parts.length; i++) {
            if (i > 0) System.out.print(", ");
            System.out.print(e.labels[i] + "=" + e.parts[i]);
        }
        System.out.println("]");
    }
}

// -----
// Synthetic data (same as prior demo, embedded for convenience)
// -----

private static final class Episode {
    final List<DeltaPosDirExtractor.Sample> selfA;
    final List<DeltaPosDirExtractor.Sample> oppB;

    Episode(List<DeltaPosDirExtractor.Sample> selfA,
List<DeltaPosDirExtractor.Sample> oppB) {
        this.selfA = selfA;
        this.oppB = oppB;
    }

    List<RelativeDeltaExtractor3D.RelSample> relAtoB3D() {
        List<RelativeDeltaExtractor3D.RelSample> out = new ArrayList<>();
        int n = Math.min(selfA.size(), oppB.size());
        for (int k = 0; k < n; k++) {
            DeltaPosDirExtractor.Sample a = selfA.get(k);
            DeltaPosDirExtractor.Sample b = oppB.get(k);

            FieldContextProvider.Vector3 selfPos = new
FieldContextProvider.Vector3(a.x, a.y, a.z);
            FieldContextProvider.Vector3 oppPos = new
FieldContextProvider.Vector3(b.x, b.y, b.z);

            FieldContextProvider.Vector3 selfDir = new
FieldContextProvider.Vector3(a.a, a.b, a.c).normalize();

            out.add(new RelativeDeltaExtractor3D.RelSample(a.t, selfPos,
oppPos, selfDir));
        }
        return out;
    }

    static void printYawPitchForA(FieldContextProvider field, Episode ep)
{
    for (int k = 0; k < ep.selfA.size() - 1; k++) {
        DeltaPosDirExtractor.Sample s0 = ep.selfA.get(k);
        DeltaPosDirExtractor.Sample s1 = ep.selfA.get(k + 1);

        FieldContextProvider.Vector3 pos0 = new
FieldContextProvider.Vector3(s0.x, s0.y, s0.z);

```

```

        FieldContextProvider.LocalFrame frame =
field.gravityAlignedFrame(s0.t, pos0);

        FieldContextProvider.Vector3 dir0 = new
FieldContextProvider.Vector3(s0.a, s0.b, s0.c);
        FieldContextProvider.Vector3 dir1 = new
FieldContextProvider.Vector3(s1.a, s1.b, s1.c);

        FieldContextProvider.YawPitchDelta yp =
field.decomposeYawPitch(dir0, dir1, frame);

        System.out.println("k=" + k
+ "   yaw(rad)=" + yp.yaw
+ "   pitch(rad)=" + yp.pitch
+ "   (t=" + s0.t + "->" + s1.t + ")");
    }
}

static Episode buildEpisode1() {
    List<DeltaPosDirExtractor.Sample> A = new ArrayList<>();
    List<DeltaPosDirExtractor.Sample> B = new ArrayList<>();

    A.add(s(0, 0, 0, 1000, 1, 0, 0));
    A.add(s(1, 120, 10, 1010, 0.98, 0.20, 0.05));
    A.add(s(2, 240, 35, 1025, 0.93, 0.35, 0.08));
    A.add(s(3, 350, 70, 1040, 0.85, 0.50, 0.10));
    A.add(s(4, 450, 115, 1050, 0.78, 0.62, 0.10));
    A.add(s(5, 540, 165, 1055, 0.70, 0.70, 0.10));

    B.add(s(0, 800, -80, 1000, -1, 0, 0));
    B.add(s(1, 700, -60, 1000, -0.98, 0.18, 0.00));
    B.add(s(2, 610, -30, 1000, -0.95, 0.30, 0.00));
    B.add(s(3, 540, 10, 1000, -0.90, 0.40, 0.00));
    B.add(s(4, 490, 60, 1000, -0.82, 0.57, 0.00));
    B.add(s(5, 465, 115, 1000, -0.70, 0.71, 0.00));

    return new Episode(A, B);
}

static Episode buildEpisode2SlightlyDifferent() {
    List<DeltaPosDirExtractor.Sample> A = new ArrayList<>();
    List<DeltaPosDirExtractor.Sample> B = new ArrayList<>();

    A.add(s(0, 0, 0, 1000, 1, 0, 0));
    A.add(s(1, 125, 5, 1008, 0.99, 0.15, 0.04));
    A.add(s(2, 255, 20, 1020, 0.97, 0.25, 0.06));
    A.add(s(3, 375, 50, 1035, 0.90, 0.42, 0.09));
    A.add(s(4, 485, 95, 1048, 0.80, 0.58, 0.10));
    A.add(s(5, 580, 150, 1055, 0.72, 0.69, 0.10));

    B.add(s(0, 800, -80, 1000, -1, 0, 0));
    B.add(s(1, 705, -62, 1000, -0.98, 0.17, 0.00));
    B.add(s(2, 620, -35, 1000, -0.96, 0.28, 0.00));
    B.add(s(3, 555, 0, 1000, -0.91, 0.40, 0.00));
    B.add(s(4, 505, 55, 1000, -0.83, 0.55, 0.00));
    B.add(s(5, 480, 112, 1000, -0.72, 0.69, 0.00));
}

```

```
        return new Episode(A, B);
    }

    private static DeltaPosDirExtractor.Sample s(double t, double x,
double y, double z,
double a, double b,
double c) {
        return new DeltaPosDirExtractor.Sample(t, x, y, z, a, b, c);
    }
}
```

关键说明（确保“体系不乱”）

- 你现有的核心 API (`RelativeMotionIrPrimitive / InteractionIrMetric`) 保持不变。
Demo++ 为了快速落地 3D relational IR，先把 3D primitive 放在 `demo` 包里 (`RelativeMotionIrPrimitive3D`)，避免破坏既有契约。
 - Evidence breakdown 同理：不替换 `MotionIrEvidence`，而是生成一个更可读的 `EvidenceBreakdown` 用于打印/解释链。
-

如果你要把 Demo++ 升级“正式化进 core 包”（下一步很自然）

我建议两个非常干净的选择：

1. **新类型**：`RelativeMotionIrPrimitive3D + InteractionIrMetric3D`（最清晰）
2. **复用现有三字段**：把 `deltaBearing` 定义为 `deltaAzimuth`，把 `deltaAspect` 改成 `deltaElevation`（不推荐，语义会混乱）

我建议走 1)。你一句话我就把 Demo++ 的 3D 版本抽成 core 级接口与实现，并把 evidence breakdown 也做成可插拔策略（仍保持最小）。

兄弟，整的很好。谢谢你。先到这。容我消化与跑一跑骨架程序。再见！

好的。我这边的交付已经把 Motion IR Stack 从方法论到可运行 Demo++ 全链路打通了：自体 Motion IR、交互 Relational IR（含 3D 版）、FieldContext（重力对齐与 yaw/pitch 解释）、Metric + Evidence（含 top-k 与维度贡献拆解）。你按现有包结构落地后，跑通 main 即可看到距离与解释链输出，后续要把 Demo++ 的 3D 交互部分“抽升”为 core 级类型与接口也非常顺滑。

你先消化、跑起来。我们下次继续推进时，你只要告诉我：你希望 3D Relational IR 进入 core 的命名与包路径（例如 `com.dbm.ir.motion.interaction3d` 或沿用 `com.dbm.ir.motion`），我就按你 repo 风格把它整理成可直接 drop-in 的正式版（含最小 JUnit4 玩具测试与 console explain printer）。

ChatGPT can make mistakes. Check important info.