

# 4

## Absolute Reference Frame

### 4.1 Valid Coordinate Reference Frames

A reference frame is a set of space coordinates, fixed in some defined way. Let us consider a closed volume  $V$  of space containing a system of  $N$  particles of matter in all possible physical states. We consider a closed volume of space in the sense that there is no transfer of mass or energy across the boundary surface of this volume; and the enclosed particles do not experience any significant force or interaction from outside this volume. Let point  $A$  be the center of mass (CoM) of these  $N$  particles and let  $K$  be a non-rotating Cartesian coordinate reference frame with its origin located at point  $A$ . In this reference frame  $K$ , let the positions of all  $N$  particles be defined to be certain function of time  $(x_i(t), y_i(t), z_i(t))$ , provided they remain bounded within the closed volume  $V$ . Since  $K$  is a reference frame with origin at the center of mass of the enclosed  $N$  particles, it is generally referred as a CoM reference frame. In a CoM reference frame, the total momentum of all of its domain particles is zero.

Within the closed volume  $V$  under consideration, total momentum and total mass-energy content of the given  $N$  particles will be conserved. We may refer this set of  $N$  particles to any coordinate reference frame, for quantifying or assigning certain measure numbers to the relative positions of these particles. But that must not alter the physical state or content of matter (e.g. mass-energy content) within the closed volume  $V$  under consideration. This requirement may be treated as a physical constraint on the choice of valid coordinate reference frames.

Out of all other inertial reference frames which could be constructed for referring the positions and velocities of given  $N$  particles within a closed volume  $V$ , the total mass-energy content measured in a CoM reference frame is the minimum. Hence, a CoM reference frame may be considered as an absolute or fixed reference frame for the given  $N$  particles contained within a closed volume  $V$ . *This is the fundamental notion of an absolute reference frame in relation to matter contained within a closed volume of space.* Since the domain particles of the reference frame  $K$  do not experience any significant force or interaction from outside its domain volume, the center of mass and hence the origin  $A$  of reference frame  $K$  will continue to remain in its state of rest or of uniform motion in the external space outside its domain volume. Hence the reference frame  $K$  can also be regarded as a unique fixed Inertial Reference frame for the closed volume under consideration.

## 4.2 International Celestial Reference System

As a consequence of the IAU 2000 resolutions,<sup>[3]</sup> the old celestial dynamical reference system, materialized by the FK5, is replaced by the International Celestial Reference System (ICRS), which consists of the Barycentric Celestial Reference Frame (BCRF) and the Geocentric Celestial Reference Frame (GCRF), both kinematically defined by the position of some extragalactic radio sources. The origin of space coordinates defining BCRF is located at the barycenter or the CoM of our solar system. The origin of space coordinates defining GCRF is located at the geocenter or the CoM of the Earth system. The new system is kinematic, because its coordinate directions are defined through the positions of extragalactic objects, whose proper motions are assumed to be negligible in comparison with the accuracy of observations.

For making a physical comparison between the BCRF and GCRF, let us introduce an unconventional term – the physical domain volume of a reference system. Roughly speaking, we are already aware of the fact that BCRF is a much bigger reference system covering the entire solar system, whereas the GCRF is comparatively a smaller reference system covering the earth-moon system. The physical domain volume of a reference system may be defined as the volume of space which contains the locations of all material particles that are used for computing the center of mass (origin of reference frame) of that system. Now, the physical domain volume of BCRF can be defined as the volume of the whole solar system within which all material particles that are co-moving with the solar system, are located. Similarly, the domain volume of GCRF can be defined as the volume of the earth-moon system within which all particles that are co-moving with the earth system, are located. Here BCRF can be regarded as an absolute or fixed reference frame in relation to the solar system whereas the GCRF, being a subset of BCRF, can be regarded as a local reference frame in relation to the solar system.

While describing the motions of terrestrial space flights, artificial satellites or the Moon, one must use the GCRF. This natural reference system moves with the Earth around the Sun. However, for describing the motions of planets, comets and inter-planetary space missions, one must use the BCRF. The task of establishing and maintaining the ICRS and its components has been assigned to the International Earth Rotation and Reference Systems Service (IERS). Major components of IERS include Technique Centers, Product Centers and Combination Centers. The main contributing observational techniques used are, International GNSS Service (IGS), International Laser Ranging Service (ILRS), International VLBI Service (IVS) and International DORIS Service.

### 4.3 Critical Observations on Relativity Principle

As per the Relativity Principle: “If a system of coordinates  $K$  is chosen so that, in relation to it, physical laws hold good in their simplest form, the same laws hold good in relation to any other system of coordinates  $K'$  moving in uniform translation relatively to  $K$ .” All non-rotating reference frames that move with uniform velocity with respect to one another, are defined as Inertial Reference Frames. The origins of all inertial reference frames will therefore move in straight lines. All inertial reference frames constitute a group and no particular member of this group can be considered a preferred reference frame.

Basically all laws of Nature will remain valid and operative independent of reference frames. However, in physics we quantify the laws of Nature, so as to represent them through certain mathematical equations involving dimensional physical parameters. We need the structure of coordinate systems and reference frames to quantify the physical parameters of relative positions, velocities, accelerations, force, momentum and kinetic energy of various interacting particles or groups of particles. To ensure that the laws of physics remain independent of the reference frame, the form or content of the mathematical equation representing any law of physics must not change with any change in the reference frame. Obviously therefore, some constraints will be required to be imposed on the choice of valid reference frames.

However, physical parameters of velocity, momentum and kinetic energy are not invariant in the inertial reference frames (IRF) in relative uniform motion. As such, some of the laws of physics, the representative equations of which include the parameters of velocity, momentum or kinetic energy, will no longer remain invariant in the inertial reference frames in relative uniform motion. Hence it is wrong to assume that all laws of physics are invariant in the group of inertial reference frames.

Whereas the principle of relativity gives the impression that infinitely many inertial reference frames are available to the user for use as per convenience; the elaborate arrangements required for establishing just one reference frame, the BCRF, must be a bit perplexing. Probably the notion of inertial reference frames, in relative uniform motion, is too simplistic, vague and misconstrued. Let us examine this notion critically:

- ***Why should reference frames be required to move at all?*** Logically it is the particles of matter that are expected to move in a reference frame. Primarily the reference frames are required for quantifying the positions of various particles located in a given region of space. A reference frame with its origin fixed at the CoM of all the particles

in the given region of space, is sufficient to quantify the positions of all such particles. We just don't need a large number of reference frames in relative uniform motion, to quantify the positions of a given set of particles. It would be utterly illogical and misleading if the IERS created 10 more celestial reference frames in relative uniform motion with respect to the BCRF.

- **Why do we need very many reference frames?** For studying the kinematic motion and dynamic interactions of an infinitely large number of particles located in a given region of space (of a closed volume  $V$ ), we need to reference their positions to a single CoM reference frame (like BCRF for the solar system). If we create a separate reference frame for each particle, the very objective of creating a reference frame will be lost. However, some local reference frames (like GCRF in the solar system) could always be created for the convenience of practical measurements of positions and velocities, provided such local measurements could ultimately be transformed to the fixed CoM reference frame.
- **Can multiple IRF in relative motion be established in BCRF?** As per the Relativity Principle all non-rotating reference frames that move with uniform velocity with respect to one another, are defined as Inertial Reference Frames. Let us consider three space ships  $S_1$ ,  $S_2$ , and  $S_3$ , moving within our solar system with *relative* uniform velocity with respect to one another. Further, let us associate reference frames  $K_1$ ,  $K_2$ , and  $K_3$  with these space ships so that these reference frames also move with *relative uniform velocity* with respect to one another. Therefore, in accordance with relativity principle, these reference frames  $K_1$ ,  $K_2$ , and  $K_3$  will be defined as inertial reference frames. But apart from *relative uniform velocity* between  $S_1S_2$ ,  $S_2S_3$ ,  $S_1S_3$ , all three space ships  $S_1$ ,  $S_2$ ,  $S_3$ , could also be moving under common gravitational acceleration in BCRF. Hence we find that inertial reference frames defined as per relativity principle could actually be moving under accelerated motion in a CoM or fixed reference frame. As such the very notion of inertial reference frames under uniform relative motion is ambiguous, impractical and misleading. Apparently this notion was introduced just for conducting hypothetical thought experiments. However, such hypothetical IRF in relative uniform motion can never be practically established within BCRF.
- **Why do we need fictitious observers on each IRF?** Actually the notion of fictitious observers is as ambiguous and misleading as the notion of IRF in relative uniform motion. Modern advancements in technology have replaced the notion of fictitious observers with

advanced electronic instrumentation while real observers watch a computer display to observe the process. For example the position and velocity measurements of a spacecraft are first recorded in the local reference frame of instrumentation and then transformed to the CoM fixed frame of the solar system, the BCRF.

- **Can relative measurements alone yield correct information?** No, relative measurements alone cannot yield true information regarding position and velocity of particles in the relevant region of space under consideration. To illustrate this point, let us consider two space ships  $S_1$  and  $S_2$  moving in the solar system. Let their position vectors in BCRF be  $\mathbf{R}_1$ ,  $\mathbf{R}_2$  and their velocity vectors be  $\mathbf{V}_1$ ,  $\mathbf{V}_2$  respectively. The dynamic motion of these space ships will obviously be governed by the parameters  $\mathbf{R}_1$ ,  $\mathbf{R}_2$  and  $\mathbf{V}_1$ ,  $\mathbf{V}_2$ . The relative separation between  $S_1$  and  $S_2$  will be given by  $\mathbf{R}_{12} = \mathbf{R}_2 - \mathbf{R}_1$  and their relative velocity will be given by  $\mathbf{V}_{12} = \mathbf{V}_2 - \mathbf{V}_1$ . If we use only relative coordinates and measure only the relative parameters  $\mathbf{R}_{12}$  and  $\mathbf{V}_{12}$  (without using BCRF) we find that the dynamic motion of the two space ships is not governed by the relative parameters  $\mathbf{R}_{12}$  and  $\mathbf{V}_{12}$ . Hence it is quite obvious that the relative measurements alone do not provide complete information as required.

#### 4.4 Relative Measurements

Let us now elaborate some relevant aspects of the relative measurements with or without the use of IRF. The term ‘relative measurement’ of object B with respect to a reference frame  $K_1$  implies the measurement of position and velocity of B relative to the origin  $A_1$  of reference frame  $K_1$ . There are two special cases of these relative measurements depending on the state of the origin of reference frame  $K_1$ .

- ◆ When the position and velocity of the origin  $A_1$  of reference frame  $K_1$  are known with respect to the relevant CoM reference frame, then the relative measurements in  $K_1$  can be regarded as local measurements, with  $K_1$  known as a local reference frame. Such local measurements constitute a necessary step in establishing absolute measurements in the relevant CoM fixed reference frame such as the BCRF. For example, the relative measurement of position and velocity of Pioneer type spacecraft from the deep space network (DSN) stations constitute such a local measurement.
- ◆ When the position and velocity of the origin  $A_1$  of reference frame  $K_1$  are not known with respect to the relevant CoM reference frame,

then all measurements in  $K_1$  can be regarded as purely relative measurements, with  $K_1$  known as a relative reference frame. If the origins  $A_1$  and  $A_2$  of two such relative reference frames  $K_1$  and  $K_2$  are known to be moving with a uniform relative velocity with respect to each other, then these relative reference frames will be known as Inertial Reference Frames of Special Relativity fame. As per the relativity principle, all IRF constitute a group and no particular member of this group can be considered a preferred reference frame. However, since a CoM fixed reference frame like BCRF can be considered a preferred reference frame for the relevant region of space, it cannot be regarded as a member of the IRF group. Hence it can be easily seen that a group of IRF can neither be practically defined, nor be established in physical space, nor be used for real practical measurements. Such a group of inertial reference frames is only a hypothetical construct used for conducting equally hypothetical ‘thought experiments’.

Finally we may conclude that a CoM reference frame may be considered as an absolute or fixed or the **preferred reference frame** for the given  $N$  particles contained within a closed volume of space. The measurements in a convenient local reference frame constitute a necessary step for establishing the absolute measurements in a relevant CoM fixed reference frame. Relative measurements alone, without reference to a CoM fixed reference frame can give misleading results. For example, relative measurement of position and velocity of a uniformly moving spacecraft, from the DSN stations may indicate as if the spacecraft is periodically accelerating towards or away from the DSN stations, which is highly misleading. Purely relative reference frames, known as inertial reference frames in SR, are only useful for conducting hypothetical thought experiments and constitute a practically redundant notion.