System Design

接下来由来介绍系统设计。

Next, I will introduce system design part.

1. about pulasr (ˈpəlˌsär)

每一个脉冲星都有自己独特的信号模型，这个模型可以用来识别不同的脉冲星。

Each pulsar has its own unique signal model, which can be used to identify different pulsars.

脉冲星的信号频率并非总是稳定，会存在一些随机的变化，年轻的脉冲星尤甚。

The signal frequency of pulsars is not always stable, there are some random changes, especially for young pulsars.

所以，脉冲星导航系统，至少需要包含两个部分，一个是带有异常值监测的信号监测系统，另一个是脉冲星数据库。

Therefore, the pulsar navigation system needs to include at least two parts, one is the signal monitoring system with abnormal value detection, and the other is the pulsar database.

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2. system design

由于脉冲星信号极为微弱，航天器通常只能依靠原子钟来记录光子到达时间（TOAs），无法记录连续脉冲信号。所以需要首先对光子TOAs进行处理，以估算脉冲到达时间（Pulse TOA）。

Since the pulsar signal is very weak, the spacecraft usually relies on an atomic clock to record the time of arrival of photons (TOAs), and cannot record continuous pulsar signals. Therefore, it is necessary to process the photon TOAs first to estimate the pulse arrival time (Pulse TOA).

估算脉冲到达时间的方法有历元折叠法和直接使用光子TOAs法，前者通过估算初始相位和周期计算脉冲TOA，后者通过最大化对数似然函数获得结果。在此过程中，需要进一步参考脉冲星数据库中的信号模型。

There are two methods to estimate the pulse arrival time:

- epoch **\ˈepək** folding method and direct use of photon TOAs method.
- The **former** calculates the pulse TOA by estimating the initial phase and period,
- and the l**atter** obtains the result by maximizing the log-likelihood function.
- In this process, it is necessary to further refer to the signal model in the pulsar database.

X射线脉冲星导航的基本原理是通过比对航天器接收到的脉冲信号到达时间（TOA）与太阳系质心（SSB）接收的同一信号的预测到达时间，来确定航天器的位置。

The basic principle of X-ray pulsar navigation is to determine the position of a spacecraft. This is done by comparing the time of arrival (TOA) of a pulsar signal received by the spacecraft with the predicted time of arrival of the same signal at the solar system barycenter (SSB).

通过测量和预测的脉冲到达时间差异，可得出航天器相对于SSB的距离。当观测到三个或更多的脉冲星时，便可利用非线性最小二乘算法几何地定位航天器。

The difference between the measured and predicted arrival times helps to calculate the spacecraft's distance relative to the SSB.

When the spacecraft observes signals from three or more pulsars, its position can be determined using a nonlinear least squares algorithm.

虽然脉冲信号的周期会引入整数模糊性，但在航天器已有精度优于300公里的初始导航解的情况下，可以忽略这种影响。

The periodic nature of the pulsar signal does cause an integer ambiguity in measurements. However, this effect can be ignored if the spacecraft already has an initial position estimate accurate to within 300 kilometers.

在每一个计算周期内，系统除了观测脉冲星信号外，还需要不断更新自身的位置向量。

At the end of each calculation cycle, the system needs to update its position vector. This is because, at the scale of the solar system, the effects of gravity fields and relativistic **\ˌrelədəˈvistik** effects on signal propagation need to be considered.

这是因为在太阳系尺度的导航中，需要考虑引力场和相对论效应对信号传播的影响。相对论效应需要考虑引力场的空间分布，并计算一个修正值来纠正由于几何和广义相对论效应引起的时间延迟。

Relativistic **\ˌrelədəˈvistik** effects require consideration of the spatial distribution of gravity fields and the calculation of a correction value to correct the time delay caused by geometric and general relativistic **\ˌrelədəˈvistik** effects.

这也提醒我们，在设计面向深空的定位与导航系统时，对于宇宙时空结构的观测是必不可少的。

This also reminds us that when designing a positioning and navigation system for deep space, observations of the cosmic spacetime structure are essential.

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3. 多种观测方程

一个航天器可以同时观测三个或更多的脉冲星，这样就可以得到多个观测方程，并确定自身的位置。 One spacecraft can observe three or more pulsars at the same time, so multiple observation equations can be obtained to determine its position.

多个航天器可以同时观测同一个脉冲星，从而确定它们组成的星座的相对位置关系。

Multiple spacecraft can observe the same pulsar at the same time, thereby determining the relative position of the constellation **\ˌkänstəˈlāSH(ə)n**.

通过比较这些航天器接收到的脉冲星信号的到达时间（TOA），可以计算出它们在脉冲星方向上的相对投影距离，并构建星座的观测向量。

By comparing the arrival times (TOA) of the pulsar signals received by these spacecraft, the relative projection distance in the direction of the pulsar can be calculated, and the observation vector of the constellation **\ˌkänstəˈlāSH(ə)n** can be constructed.

这种方法能够有效提高星座整体的定位精度，为协同导航提供关键数据。

This method can effectively improve the positioning accuracy of the constellation **\ˌkänstəˈlāSH(ə)n** as a whole and provide key data for cooperative navigation.

我们还可以考虑融合多种数据源以提高定位精度，比如地面测量数据、星座观测数据、恒星观测数据等。

We can also consider integrating multiple data sources to improve positioning accuracy, such as ground measurement data, constellation observation data, and star observation data.

4. 跨星系导航

> - 1 l.y = 9.461e+12 km = 9.461e+15 m = 63240 AU

比邻星距离地球约**4.24光年**（约268,137 AU），是离我们最近的恒星系统。假设我们以当前最快的无人探测器（如“旅行者1号”约17 km/s）的速度前往比邻星，并考虑加速和减速操作，大约需要**74,000年**才能抵达。

The distance from the Earth to Proxima Centauri **\ˈprɑːksɪmə sɛnˈtɔri** is about **four point two four light years** (about two hundred and sixty-eight thousand AU), which is the closest star system to us.

Assuming that we travel to Proxima Centauri at the current fastest unmanned probe speed (such as Voyager 1, about seventeen kilometers per second), and considering acceleration and deceleration operations, it will take about **seventy-four thousand years** to arrive.

假设探测器从比邻星出发，最终进入太阳系时的最大允许误差可做如下估算：太阳系八大行星主要分布在距太阳100 AU以内的球体内，因此，进入太阳系时的允许偏差范围可设为100 AU以内。由此推算，抵达太阳系附近时需将定位精度控制在约**76.9角秒**（约3.73×10^{-4}弧度），确保探测器能够进入行星分布范围内。

Assuming that the probe departs from Proxima Centauri, the maximum allowable error when entering the solar system can be estimated as follows: - the eight major planets of the solar system are mainly distributed within a sphere within 100 AU of the Sun. - Therefore, the allowable deviation range when entering the solar system can be set to within 100 AU. - It is estimated that when arriving near the solar system, the positioning accuracy needs to be controlled to about **76.9 arc seconds** (about 3.73×10^{-4} radians) to ensure that the probe can enter the planet distribution range.

在如此长的航程中，初期仅需大致的方向，而临近目标时则需极高的定位精度。因此，我们需要一个能在整个航程中提供分级精度的定位系统，类似瓦片地图的逐步细化方式，以满足不同航程阶段的需求，确保探测器准确进入目标星系。

In such a long journey, only a rough direction is needed at the beginning, and extremely high positioning accuracy is required when approaching the target.

to meet the needs of different journey stages and ensure that the probe accurately enters the target star system, we need a positioning system that can provide hierarchical **\ˌhī(ə)ˈrärkək(ə)l** accuracy throughout the journey, similar to the step-by-step refinement method of tile maps.

5. 系统框架

若我们想要设计这种可以在星际空间中提供定位服务的系统，就可以考虑以下框架。

If we want to design a system that can provide positioning services in interstellar **\ˌin(t)ərˈstelər** space, we can consider the following framework.