Investigation of Relativistic Spaceflight through Special Relativity

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Abstract

Special Relativity is a theory that describes constant-velocity motion at speeds approaching the speed of light c, the main effects of which are time (and thus distance and speed) being relative to the observer. It was developed in 1905 by Albert Einstein and is fundamental to calculating the motion and observations of observers at relativistic speeds.

In this paper, we investigate the impact of relativistic speeds on communication and navigation in spaceflight and describe the theoretical feasibility of a mission into deep space.

1 Introduction to Relativity

Special relativity is founded on the postulate that the speed of light is constant for all observers in all reference frames. Thus, if two observers are moving at different speeds relative to each other (they are in different inertial reference frames) then their measurements of the speed of light must regardless be the same.

Consequently, the measurements of time and distance that the observers take must change to compensate for this disparity. This is governed by the time- and length-dilation equations which relate the time t and position x of one observer to the time t' and position x' of a second observer, which moves at a relative speed v to the first observer. These equations are seen below:

$$x' = \gamma(x - vt)$$
$$t' = \gamma(t - \frac{v}{c^2}x)$$

where γ is the Lorentz factor $\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$, which grows asymptotically as $v \to c$.

These definitions introduce two important concepts. First, the path through space and time of an observer is referred to as its *worldline*, which determines the relativistic effects on that observer's observations. Secondly, as time is relative, an important distinction must be made between *co-ordinate time* and *proper time.*

Proper time is the time as measured by a certain observer (and thus subject to time dilation.) Conversely, co-ordinate time is the time as measured by an observer at rest. Co-ordinate time is an important concept in measuring timings objectively within a given reference frame.

2 Relativistic Communication

If a spacecraft is not fully autonomous, communication with both its origin and its destination will be required to maintain proper operation. However, relativistic effects engender a variety of novel problems in photon-based communication. Here we consider a mission with acceleration $\alpha = g$ and a cruise profile of constant acceleration followed instantly by constant deceleration, thereby producing a symmetric flight path.

2.1 The Event Horizon

An important characteristic of a cruise profile is its event horizon $t_h = c/\alpha$. It represents the latest time at which a photon emission can be detected or received within the time frame of the mission. We consider these photons to be *productive.* As shown in fig. 1, for an indefinitely accelerating cruise profile, any photon emission after t_h is parallel to and never intercepts the worldline of the spacecraft, and thus cannot be detected.

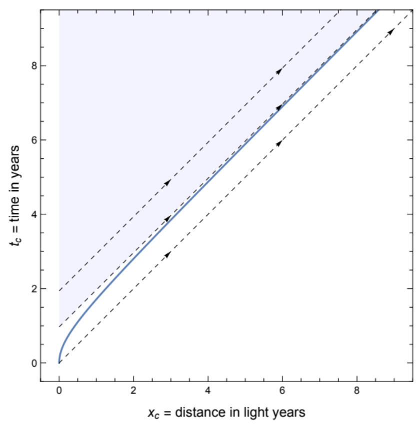

Figure 1: Photon emissions at $t \in \{0, t_h, 2t_h\}$. Dashed lines represent photon trajectories and the solid blue lines represents the spacecraft's worldline. [4]

2.2 Productive Photon Emissions

Because the spacecraft undergoes a deceleration phase, the latter part of its flight path is a mirror image of the initial acceleration phase. Consequently, the time frame for productive emissions is around $2t_h$, and these emissions are detected only briefly after leaving the origin or before landing at the destination. For the remainder of the mission, the spacecraft cannot receive communications from the origin.

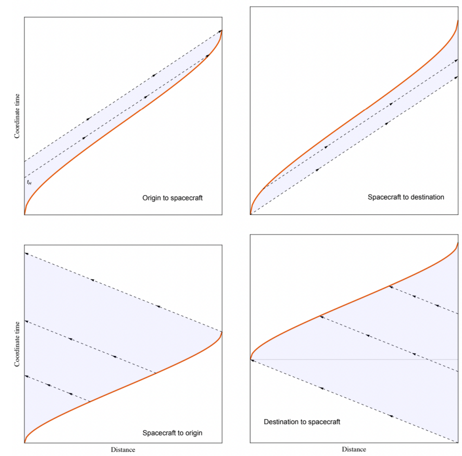

Figure 2: Timing constraints on productive photon trajectories. The solid line represents the spacecraft, while the blue area and dashed lines represent the possible ensemble of photon trajectories and example trajectories respectively. [4]

Conversely, communication from the spacecraft to the origin is productive for about double the proper time of the craft, as photons travel perpendicular to the craft rather than parallel to it. However, due to relativistic time dilation of the spacecraft's clock, these emissions are received over a time span orders of magnitude larger than they were emitted in.

2.3 Communication Delays

As shown in fig. 3, communication from the origin to the spacecraft is impacted by the communication blackout at t_h, which is represented by the first dashed line. The graph is tangent here, as photons must now be detected in the craft's deceleration phase.

Concerning communication in the reverse direction, the origin will receive communications from the spacecraft continuously. However, due to time dilation of the spacecraft's clock, the reception period (as measured by the origin) will be orders of magnitude larger than the emission period (as measured by the spacecraft), meaning these communications are "warped".

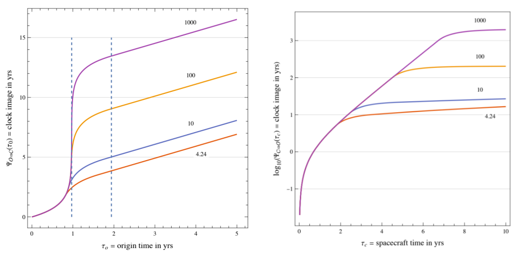

Figure 3: Communication delays from (left to right) the origin to spacecraft; and spacecraft to origin. Separate lines represent missions of different distances. Dashed lines represent t_h and $2t_h$ respectively. [4]

3 Relativistic Navigation

As outlined in the previous section, there is a high premium on any external communication from the spacecraft. Thus, near-complete autonomy will be required for a successful mission, a large component of which is navigation.

The main challenge in relativistic navigation is accurate knowledge of a spacecraft's position. If a spacecraft is to be autonomous or adaptable while navigating deep space, it must have a positioning system which can function independent of systems on Earth and in relativistic reference frames.

The most obvious solution is to use the spacecraft's internal measurements in order to make a position estimate. However, due to the accumulating error in measurements, this method is too inaccurate for longer journeys [1].

3.1 Pulsar Positioning

Pulsars are rapidly rotating neutron stars which emit electromagnetic waves solely from their magnetic poles. Thus, an observer receives an extremely uniform, periodic pulse once every rotation which can act as a precise reference point. If a spacecraft receives pulses from enough distinct pulsars, this information can be used to reconstruct their position.

3.2 The Catalog

To usefully observe pulsars we first require an accurate catalog of them, such as the Gaia catalog [1]. This consists of a set of positions, velocities and pulse profiles (see section 3.3) for each pulsar.

The catalog must be measured from some inertial reference frame. A common candidate is solar system barycenter (SSB) frame, which is centered about the solar system's center of mass and measures time in barycentric dynamic time [5].

3.3 Mathematical Transformations

In order to compare the emissions TOAs (time of arrival) with our pulsar catalog, we must be able to predict these pulses. The pulse intensity at a given time t is governed by a Taylor Series expansion about a reference epoch t_0 [5, 3]

$$\Phi(t) = \Phi(t_0) + f(t - t_0) + \frac{\dot{f}}{2}(t - t_0)^2 + \frac{\ddot{f}}{6}(t - t_0)^3 \quad (1)$$

However, this formula references co-ordinate time t relative to the SSB. Accordingly, we must first transform our observations from our inertial frame to the SSB frame.

3.3.1 Velocity Correction

Given an observer with relative velocity v to a non-gravitational inertial frame, this frame's co-ordinate time t and their proper time τ are related by

$$(t - t_0) = (\tau - \tau_0) + \int_{\tau_0}^{\tau} \frac{1}{2}\left(\frac{v}{c}\right)^2 \mathrm{d}\tau$$

This integral can be solved with knowledge of the spacecraft's trajectory, which yields the co-ordinate time of the spacecraft [5].

3.3.2 Position Correction

The position of the spacecraft relative to the SSB additionally impacts the TOA of pulses. Given the direction from the SSB $\hat{n}$ of a given pulsar and the position of the spacecraft r, the observed TOAs for this pulsar are related by

$$t_{SSB} = t_{SC} + \frac{\hat{n} \cdot r}{c} \quad (2)$$

3.4 Delta-correction

Using a spacecraft position r that deviates from the true position in eq. (2) will result in a difference between the predicted and observed TOA of a given pulse. This difference can be used to iteratively update the assumed position of the spacecraft until it matches the observed TOAs [2].

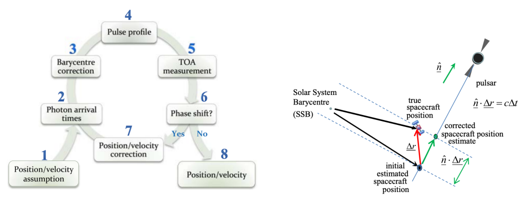

Figure 4: From left to right: Iterative method for position determination via pulsar observation. The existence of phase shift is equivalent to an offset between predicted and observed TOA [2]; A simplified model of measuring the position error of a spacecraft in the direction of a pulsar. Note that the corrected and true positions are distinct [6]

Using an initial prediction of the spacecraft's position, either generated by systems on Earth or knowledge of the craft's motion (see [5, 2]), we let the errors in our prediction be defined by

$$\delta r = r - \tilde{r}$$
$$\delta t_{SSB} = t_{SSB} - \tilde{t}_{SSb}$$
$$\delta t_{SC} = t_{SC} - \tilde{t}_{SC}$$

Again, assuming that there are no gravitational effects, it then follows from eq. (2) that

$$\delta t_{SSB} - \delta t_{SC} = \frac{\hat{n} \cdot \delta r}{c} \tag{3}$$

All values except δr can be calculated using predicted and observed pulses, thus eq. (3) can be rearranged to yield a correction to the spacecraft's position in the line of sight of the pulsar [5]. Repeating these calculations for at least 3 linearly independent pulsars allows us to solve for the spacecraft's 3-dimensional position [7].

3.5 Ambiguity

Since the observed pulses are periodic, ambiguous solutions may occur. However, measuring multiple pulsars can help us avoid degenerate cases as shown in fig. 5

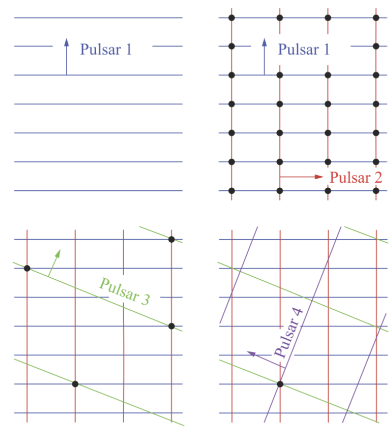

Figure 5: Solving the ambiguity problem via overlapping pulses. Each line represents a wavefront of constant phase from a given pulsar [2]

4 Results

1. In terms of relativistic navigation, the available research in this area is promising. Using existing technology and information, it is theoretically possible to create a very accurate and reliable positioning system that solves most issues common to Earth-based or classic approaches.
2. Concerning relativistic communication, the effects of relativity are more pronounced. Communication is extremely delayed or impossible during large parts of the flight. This would require a much greater degree of autonomy than current missions enjoy. However, this is by no means impossible.

5 Conclusions

In this paper, we have explored and utilised the theory of relativity along with existing research to investigate both communication and navigation in relativistic spaceflight. The available literature indicates that, while numerous novel approaches are required to facilitate this (e.g. positions systems and autonomy during communication blackouts), this task is altogether feasible in the long term.

References

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