TIME AND FREQUENCY REQUIREMENT FOR THE EARTH AND OCEAN PHYSICS APPLICATIONS PROGRAM*

Friedrich O. von Bun
Goddard Space Flight Center

My talk will outline some of the time and frequency requirements we have for the Earth and Ocean Physics Applications Program (EOPAP). I will divide my talk into two major parts, since many of you may not know what this program is about. First I will explain what the program is and what it consists of, and then I will try to answer the question: "Why do we need certain requirements in time and frequency to accomplish these metric tasks we have given ourselves?"

I have to mention at this time that EOPAP is not yet fully approved by NASA, although we are lucky to have gotten our first spacecraft at least to the Bureau of the Budget. As you may know, it is difficult at this time to start anything new, so I cannot complain.

First, I will talk about the program itself, and the accuracies needed as far as frequency and time are concerned. Then I will try to translate these requirements, which come from ultra-precision orbital requirements, into those of time and frequency. Actually there are three parts to this, as you can see in Figure 1.

The Earth and Ocean Physics Applications Program has specific goals, and we need to perform specific experiments to achieve these goals. We must also fly certain spacecraft to reach these goals. We also have certain accuracy requirements which relate directly to time-frequency requirements.

A. THE EOPAP
- GOALS AND EXPERIMENTS
- SPACECRAFT

B. ACCURACIES NEEDED FOR THE PROGRAM
- MEASUREMENT REQUIREMENTS SUMMARY

C. TRANSLATE THESE REQUIREMENTS INTO
- TIME
- FREQUENCY

$\left.\begin{array}{l}\text{TIME}\\ \text{FREQUENCY}\end{array}\right\}$ REQUIREMENTS

Figure 1. The Earth and Ocean Physics Applications Program.

*This is the edited transcript of the recorded oral presentation.

The program consists of two major parts (Figure 2), namely earth dynamics and ocean dynamics. I'll explain a little bit later on what I mean by that, and, as I mentioned before, I will talk about the goals and the spacecraft, including the launch schedule.

MAJOR GOALS AND EXPERIMENTS

- EARTH DYNAMICS
- OCEAN DYNAMICS

SPACECRAFT AND LAUNCH SCHEDULE

Figure 2. The main parts of the program.

The major goals in earth dynamics are shown in Figure 3 and include earthquake hazard assessment and alleviation. Can we do something with present spacecraft or future spacecraft? What have we learned over the last ten years on space techniques which we can apply to problems we have on the ground? That is the driving force, really, for that program.

To give you an example, we are presently performing an experiment in the San Andreas Fault area to measure the motion between the American plate and the Pacific plate, utilizing laser techniques, laser-ranging techniques to be more accurate, with the BEC spacecraft equipped with laser corner reflectors.

Some time ago -- I think about a year ago -- we finished a polar motion experiment. We determined the motion of the pole to an accuracy of about one meter, utilizing only one single laser station and the BEC spacecraft. We could do this within six hours to the accuracy of one meter.

On global surveying and mapping, we are trying to determine the gravity field, particularly for the ocean dynamics program. We have considerably improved our station locations, particularly for the laser station. We have also improved the magnetic field for surveying and mapping.

EARTHQUAKE HAZARD ASSESSMENT AND ALLEVIATION

- SAN ANDREAS FAULT EXPERIMENT (SAFE, LASER, VLBI)
- PLATE MOTION EXPERIMENT (VLBI, LASER) (U.S., JAPAN)
- SOLID EARTH TIDES (LASER, ATS-G)
- POLAR MOTION (LASER, VLBI)
- UT-1 (VLBI, LASER)

GLOBAL SURVEYING AND MAPPING

- GRAVITY FIELD DETERMINATION, R, $\dot{R}$, $\measuredangle$ LASER, GEM1-4 (SST, ALTIMETER)
- GEOID AND GRAVITY FINE STRUCTURE (ALTIMETER, R, $\dot{R}$, $\measuredangle$ (SST)
- MAGNETIC FIELD DETERMINATION, MAGNETOM, ORBIT
- INTERNATIONAL SATELLITE GEODESY EXPERIMENT, $\measuredangle$ ISAGEX, R, $\dot{R}$, LASER

Figure 3. Major goals and experiments in the earth dynamics area of EOPAP.

The major experiments and goals in the area of ocean dynamics (Figure 4) are twofold. We try to determine the currents and the circulation by measuring the geostrophic uplift in the ocean. For this we would need an altimeter with at least a high resolution to, say, 10 centimeters.

As you may know, in 1974, we are flying the GEOS-C spacecraft, which will be equipped with an altimeter with an accuracy of about a meter or two. In addition, this spacecraft will be tracked from the ATS-F spacecraft by means of satellite-to-satellite tracking (SST) to help us in the orbit determination.

This will be the first satellite equipped with an altimeter which may give us a more detailed view of the ocean, particularly the ocean surface or, more specifically, the variation of the mean ocean surface. We will evaluate the ocean surface condition from the altimeter data. We may further get the sea state, the wind direction, and storm searches, all important factors, for instance, for shipping.

OCEAN CURRENTS AND CIRCULATION

- OCEAN SURFACE CONDITIONS, GEOID, SLOPES, (ALT., SST, OTHERS)
- GENERAL CURRENTS AND CIRCULATION (ALT., TRACERS, SST, OTHERS)
- OPEN OCEAN TIDES, TSUNAMIES (ALT., SST, OTHERS)

OCEAN SURFACE CONDITION MONITORING

- SEA STATE, WAVE DIRECTION (ALT., SCATT., SST, OTHERS)
- SURFACE WINDS, MAGNITUDE, DIRECTION (ALT., SCATT., SST, OTHERS)
- STORM SURGES (ALT., SST, OTHERS)

Figure 4. Major goals and experiments in the ocean dynamics area of EOPAP.

Now let me give you an idea (Figure 5) of measurements we're trying to make in order to accomplish the tasks outlined. We have to determine, for instance, the crustal motion, say to within one centimeter a year, if we want to determine what energy is stored in fault lines.

MEASUREMENT	ACCURACY
• CRUSTAL MOTION	1 CM/YEAR
• POLAR MOTION, EARTH ROTATION	2 CM/0.5 DAY
• SATELLITE ORBITS	10 CM
• GRAVITY FIELD/GEOID	10 CM
• SEA SURFACE TOPOGRAPHY	10 CM
• SEA STATE/WAVE HEIGHT	$1 \div 3$ M
• SURFACE WINDS	$2 \div 5$ M/S, $< 20^\circ$
• MAGNETIC FIELD	2 GAMMA, 0.5 ARCMIN

Figure 5. Measurements requirements summary.

We would like to determine polar motion to two centimeters' accuracy in a half a day's time. There seems to exist a correlation between polar motion and earthquakes. To do all this we need extremely precise satellite orbits (gravity field). Further, we need to have the sea state and wave height determined between, say, one and three meters. The surface winds we would like to determine to five meters a second, with a directional angle of at least 20 degrees; less if we can. We will further try to determine the magnetic field of the earth to about ± two gamma and a half-minute of arc. Right now we know the magnetic field to a few gammas but only the magnitude, not the direction.

In order to do this we have come up with a couple of flight missions, shown in Figure 6. And as I mentioned before, the first spacecraft, which is a large geodetic satellite, is at the Bureau of the Budget. This satellite is just a simple, heavy ball equipped with laser corner reflectors, which will have a polar orbit of roughly 3000 to 5000 kilometers and will act as a reflecting reference station in space. We hope to determine the orbit very accurately, say in the 10-centimeter range, so that we can determine motion of the poles, UT-1, and tectronic plate motions.

The next satellite we are planning is a SEASAT-1 – which stands for sea satellite – and which is, in essence, an oceanographic spacecraft equipped with a very accurate, perhaps a 30- to 50-centimeter-type altimeter, to determine ocean surface variation. Obviously other instruments will be carried, not of interest as far as time and frequency are concerned.

The next spacecraft is the Geopause, like "magnetopause." It means the satellite is so far away that it is out of the "noise field" of the gravity of the earth. At 30,000 kilometers, only six or seven of the gravity coefficients of the earth play a role; for a near-earth spacecraft at say 300-kilometer height, one needs perhaps 600 to 900 coefficients to determine a very accurate orbit. This is why we are going far out, and using that spacecraft as an "anchor" station to measure range rate using SST techniques. By doing so we can determine the exact variation of that low-orbiting satellite. SEASAT-2 is thought of as an operational sea satellite.

LAGEOS			S		▲						
SEASAT-1			S			▲					
GEOPAUSE				S				▲			
GRAVSAT				S				▲			
SEASAT-2							S				▲
CAL YEAR	72	73	74	75	76	77	78	79	80	81	82

S = START
▲ = LAUNCH

Figure 6. EOPAP spacecraft.

As you can see, the program plan covers the years up to 1982, but at the present time we are just talking about the first 1973 spacecraft, LAGEOS, and SEASAT-1.

This should give you an idea what we want to do, and the reason why -apply what we know and have learned in the past to problems we have on earth.

Let me try now to translate orbital accuracies into those of time and frequency. Take the orbit, say, of the LAGEOS, and we are talking about a two-centimeter range, which means we need a timing accuracy on the order of two or three microseconds (Figure 7).

What is the time synchronization needed if we perform range and range rate tracking from a satellite which is in a nearly synchronous orbit? Again we go through some basic arithmetic and we come up with roughly a microsecond, as the calculations shown in Figure 8 demonstrate. In order to sense the gravity variation of the earth's field by observing variations in the height of the low-orbiting satellite we need this kind of accuracy, and we hope with the Geopause spacecraft in orbit we can achieve this goal.

We have already planned – and hardware is being built – an ATS/Nimbus satellite-to-satellite tracking experiment, and hope to get 0.07 centimeter per second. And these spacecraft will be in orbit by 1974. Thus we will have some idea of what we can do and cannot do in the near future.

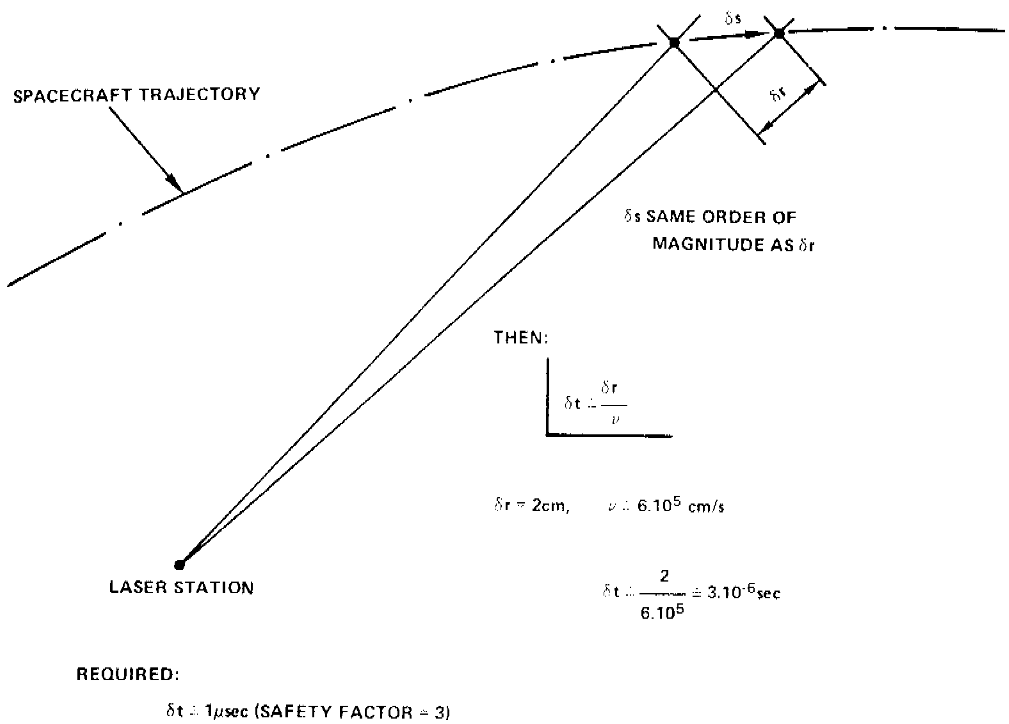

Figure 7. Time synchronization for orbital range tracking with LAGEOS.

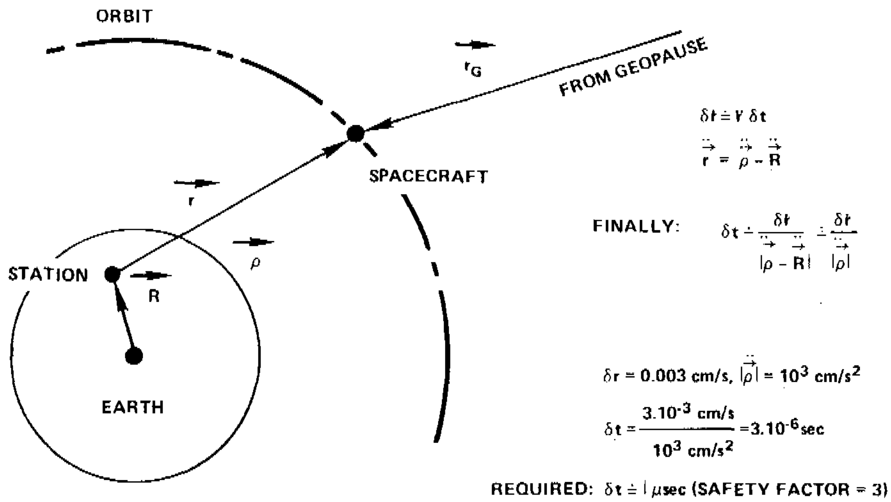

Figure 8. Time synchronization for orbital range-rate tracking with Geopause.

What time synchronization do we need, for instance, if we fly an altimeter (Figure 9)? And here we see it is a rather relaxed one. For an altimeter spacecraft experiment we need only one-third of a millisecond time synchronization between the stations, because it is really not too important where the spacecraft is in a horizontal direction. A millisecond corresponds to about one meter, yet the footprint is 10^4 times larger. This results from the variation of the height of the spacecraft, since one always has an orbit with a finite eccentricity.

HEIGHT VARIATION: $\dot{h} \doteq \nu . e \sin \eta$ **for** $e \leqslant 0.1$

AND: $$\delta t \doteq \frac{\delta h}{\dot{h}}$$

FOR: $\nu = 8.10^5$ cm/s, $e=0.0125$, $\dot{h} = 100$ m/s

USING: $\delta h = 10$ cm

$$\delta t = 10^{-3} \text{ sec} = 1 \text{ msec}$$

REQUIRED: $\delta t \doteq 1/3$ **msec (SAFETY FACTOR = 3)**

Figure 9. Time synchronization for a radar altimeter.

What frequency stability do we need if we have a two-way ranging system as we have right now on the Goddard network? We need a frequency stability $\delta\nu/\nu$, as in Figure 10, of 10^9, say over one second, again with the safety factor of three, if we want to determine a range rate to, say, 0.003 centimeter per second.

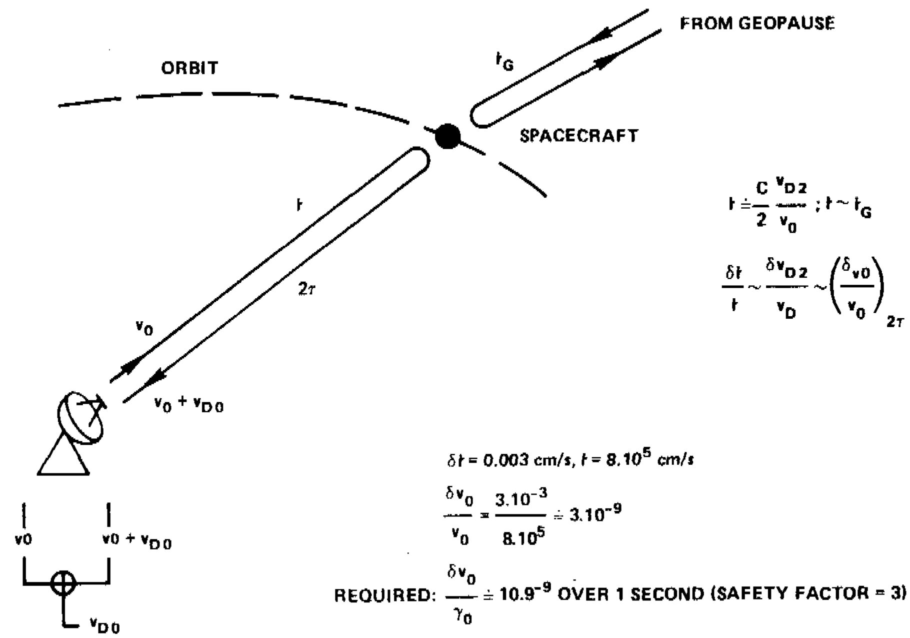

Figure 10. Frequency stability for a two-way range-rate system.

The frequency synchronization for a three-way ranging system is more stringent, as Figure 11 indicates. If one sends a signal up and receives it someplace else, any time bias error would introduce a range rate error. If I don't know the other stations' frequency, I would interpret the error as a doppler shift. In this case, we would need one part in 10^{13}, again with a safety factor of three.

1. **FREQUENCY STABILITY PROBLEM SAME AS BEFORE**
2. **FREQUENCY OFFSET BETWEEN STATION 1 AND 2 WILL NOW BE INTERPRETED AS RANGE RATE' THUS INTRODUCING AN ERROR:**

$$\left(\frac{\delta \nu_{12}}{\nu_0}\right) \doteq 2 \frac{\delta t}{C}$$

$\delta t = 3.10^{-3}$ cm/s, $C = 3.10^{10}$ cm/s, $\nu_0 = 2.10^9$ Hz

$$\frac{\delta \nu_{12}}{\nu_0} = 2 \frac{3.10^{-3}}{3.10^{10}} \doteq 2.10^{-13}$$

$$\text{REQUIRED: } \frac{\delta \nu_{12}}{\nu_0} \leqslant 10^{-13} \text{ (SAFETY FACTOR = 3)}$$

Figure 11. Frequency synchronization for a three-way range-rate system.

Figure 12 summarizes what I just said and tells what time synchronization we need for range and range-rate stations, as well as for satellite-to-satellite tracking. We're looking forward to, say, a one microsecond time synchronization between tracking stations. The frequency stability for a two-way range-rate system needs to be one part in 10^9, and a frequency synchronization for a three-way system needs to be one part in 10^{13}.

I hope I have given you some idea what we need for the new program both in frequency and in time synchronization.

- **TIME SYNCHRONIZATION:** $\delta t \doteq 1\ \mu sec$

  (FOR RANGE AND RANGE-RATE STATIONS, SATELLITE-TO-SATELLITE TRACKING)

- **FREQUENCY STABILITY:** $\frac{\delta v_0}{v_0} \leqslant 10^{-9}$ (1 sec)

  (FOR TWO-WAY RANGE RATE)

- **FREQUENCY SYNCHRONIZATION:** $\frac{\delta v_{12}}{v_0} \leqslant 10^{-13}$

  (FOR THREE-WAY RANGE RATE)

Figure 12. Summary of EOPAP requirements.

DR. WINKLER:

I think I have to ask a question here. If we understand your last requirement, one part to 10^{13}, is that absolute accuracy? Or is it frequency stability, or synchronization of . . . ?

DR. VON BUN:

It's really a frequency offset, and not an absolute accuracy.

DR. WINKLER:

So that would be frequency difference in the oscillators, and it has to be maintained to be within that?

DR. VON BUN:

Yes.

DR. WINKLER:

I see. Over what period of time?

DR. VON BUN:

Over the interval in which you make the measurements (minutes to hours, for example).

DR. WINKLER:

Over seconds?

DR. VON BUN:

No, over this measuring interval.

DR. WINKLER:

I understand. But that means you will have to use hydrogen masers at these stations?

DR. VON BUN:

That's right. We have actually used hydrogen masers at our tracking stations.