Quasi real-time positioning of spacecrafts using the Internet VLBI system

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Abstract. We started the development of a quasi real time technique for spacecraft positioning by using the Internet-VLBI system in collaboration with the Institute of Space and Astronautical Science (ISAS). A series of VLBI observations receiving the signals from Japanese spacecraft GEOTAIL and NOZOMI have been carried out since June, 2002 to establish an observation method and to evaluate the measurement accuracy. At present it is possible to obtain the time delay which is a VLBI observable to use for satellite positioning within a few days after observations. Orbital determination software is under development in parallel to the improvement of observation data processing software. Phase delay measurement software is also under development to increase the measurement accuracy.

Keywords: Internet VLBI, Delta VLBI

1. Introduction

Communications Research Laboratory (CRL) has promoted a research on the quasi real-time spacecraft positioning by adopting a delta VLBI technique with the use of the Internet (Fig.1). A general-purpose VLBI system using a PC for data acquisition and the Internet protocol (IP) for data transmission has been developed as a part of this project. The system is called Internet VLBI or IP-VLBI system (Kondo et al., 2002).

The IP-VLBI system aims at a fully real-time VLBI operation from data acquisition to data reduction. At present time, automated observations and off-line correlation processing are available. A number of VLBI sessions observing telmetry signals from Japanese spacecrafts, GEOTAIL (Nishida, 1994) or NOZOMI (Yamamoto and Tsuruda, 1998), have been carried out using the IP-VLBI system since June, 2002 in collaboration with the Institute of Space and Astronautical Science of Japan (ISAS) and the National Astronomical Observatory of Japan (NAO) to check automatic observation software and to evaluate the accuracy of observed delay.

This paper presents the design of IP-VLBI system, fringes observed for various kinds of telemetry mode, and observed delay accuracy.

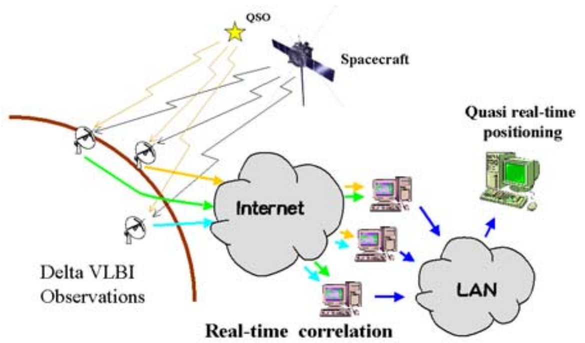

Fig.1. Concept of quasi real-time positioning of spacecraft using the Internet VLBI system.

Table 1. Specifications of a PCI VSSP board.

Reference signals	10MHz(+10dBm), 1PPS (TTL)
Number of input channels	max 4 ch
A/D resolutions	1, 2, 4, 8 bits
Sampling frequencies	40kHz, 100KHz, 200kHz, 1MHz, 2MHz, 4MHz, 8MHz, 16MHz

2. Internet VLBI system (IP-VLBI)

A new real-time VLBI system using Internet protocol (IP) technology has been developed to reduce network-cost and to expand connecting VLBI sites compared with an asynchronous transfer mode (ATM) based on a real-time VLBI system developed by the Keystone VLBI project (Koyama et al., 1998). We call this system "Internet VLBI" or "IP-VLBI".

The IP-VLBI system consists of a PC equipped with a PCI-bus Versatile Scientific Sampling Processor (VSSP) board. Table 1 summarizes specifications of VSSP board. The board has two reference signal inputs (10 MHz and 1 PPS signals) and four analog data input channels. Sampling frequency is from 40 kHz up to 16 MHz and A/D conversion resolution is from 1 bit to 8 bits. They are all programmable but maximum data rate is limited by the combination of CPU motherboard and PCI bus speed. So far we have attained the throughput of 64 Mbps stably. It corresponds to 4ch X 1bit X 16MHz sampling or 4ch X 4bit X 4MHz sampling, and so on.

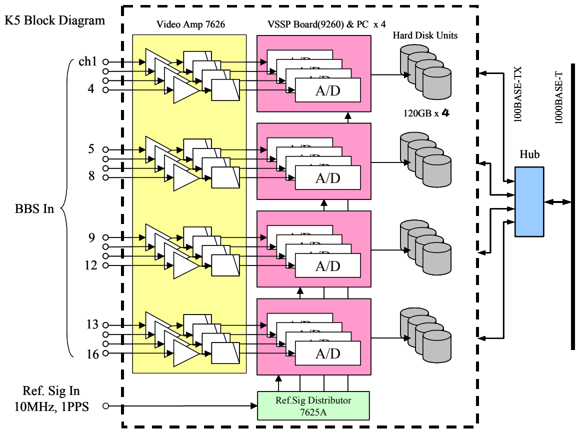

Fig.2. A schematic block diagram of K5-VSSP system.

We are expecting the increase of the maximum data rate optimistically, because the performance of PC and peripherals evolve quickly these days. A 64 bit-header data including precise time tag is inserted into the digital data stream every second. Sampled data are stored on a hard disk drive (HDD) and/or transmitted to a remote PC where software correlation processing is carried out. Correlated data are further processed to get multi-band group delay etc. A driver program for the VSSP board was first developed for FreeBSD system, but now it is available for Linux and Windows 2000 system.

The IP-VLBI system aims at taking over current geodetic VLBI system that receives 14 or 16 frequency channels at S and X bands. As a VSSP board on a PC can input 4 channel data, 4 PCs can cover channels necessary for a geodetic VLBI

Fig.3. A K5-VSSP prototype.

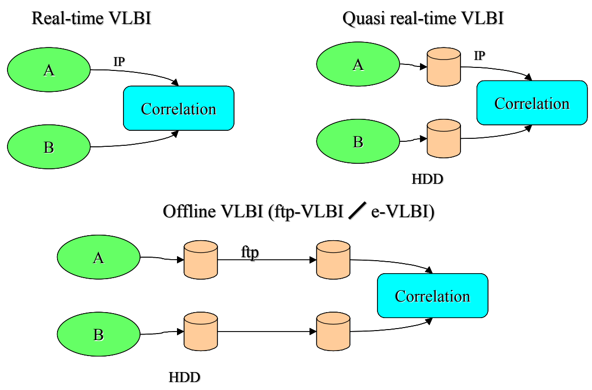

Fig.4. Supposed Operational Mode of the Internet VLBI

observation. The system assembled this way is named "K5-VSSP". A block diagram of K5-VSSP is shown in Fig.2. Each PC has four 120 GB HDDs for data storage, then total storage capacity is 1.92 TB. This corresponds to a 60000 sec scan length with 256 Mbps observation and is usually enough size to store a 24-hour (86400 sec) geodetic VLBI session, because antenna slewing time to switch radio sources is excluded. A picture of prototype K5-VSSP is shown in Fig.3.

Supposed operational mode of the Internet VLBI (K5) system is summarized in Fig.4. Although our final goal is real-time operation, off-line operation (FTP-based operation) and/or quasi real-time operation are the first requirement of system development. Regarding off-line operation, full automated observation is now available with K5.

Further system development is continued to realize a real-time VLBI operation.

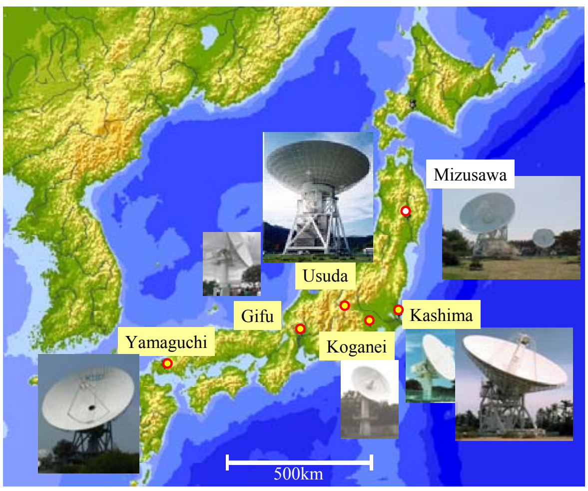

Fig.5 The location of stations participated in VLBI observations for satellite positioning.

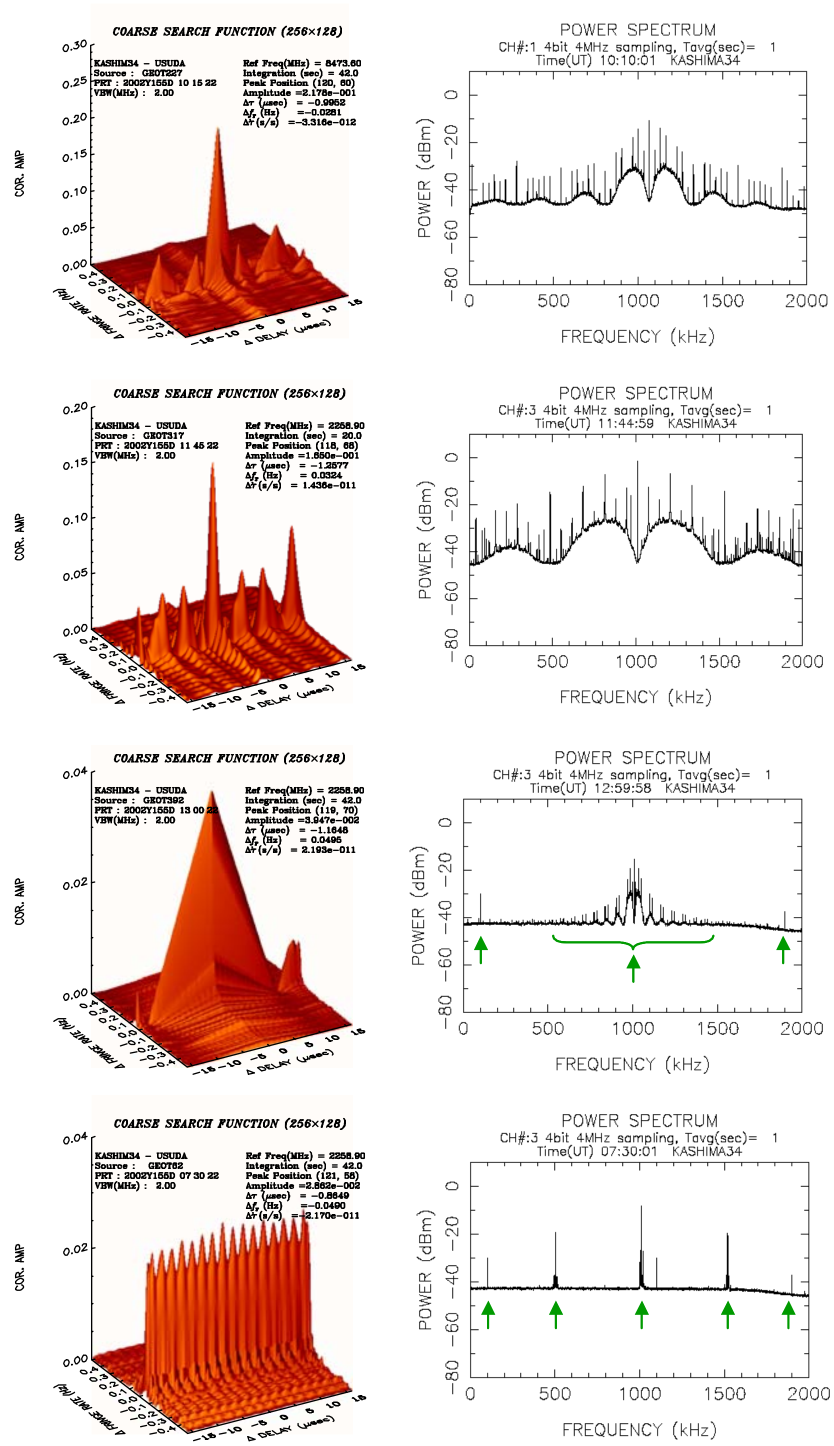

Fig.6. Fringes detected for GEOTAIL. Group delays can be determined without ambiguity excepting the lowest panel case.

3. Delta VLBI observations

The difference in the signal time of arrival at the two stations, referred to as the delay, is a VLBI's measure observable. This delay is composed of a geometric delay and other delays, such as, propagation medium delay, instrumental delays, clock offsets, etc. If a position well-known source is located nearby a target (spacecraft), differencing both observations will reduce common delays and only differential geometric delay applicable to a spacecraft position measurement

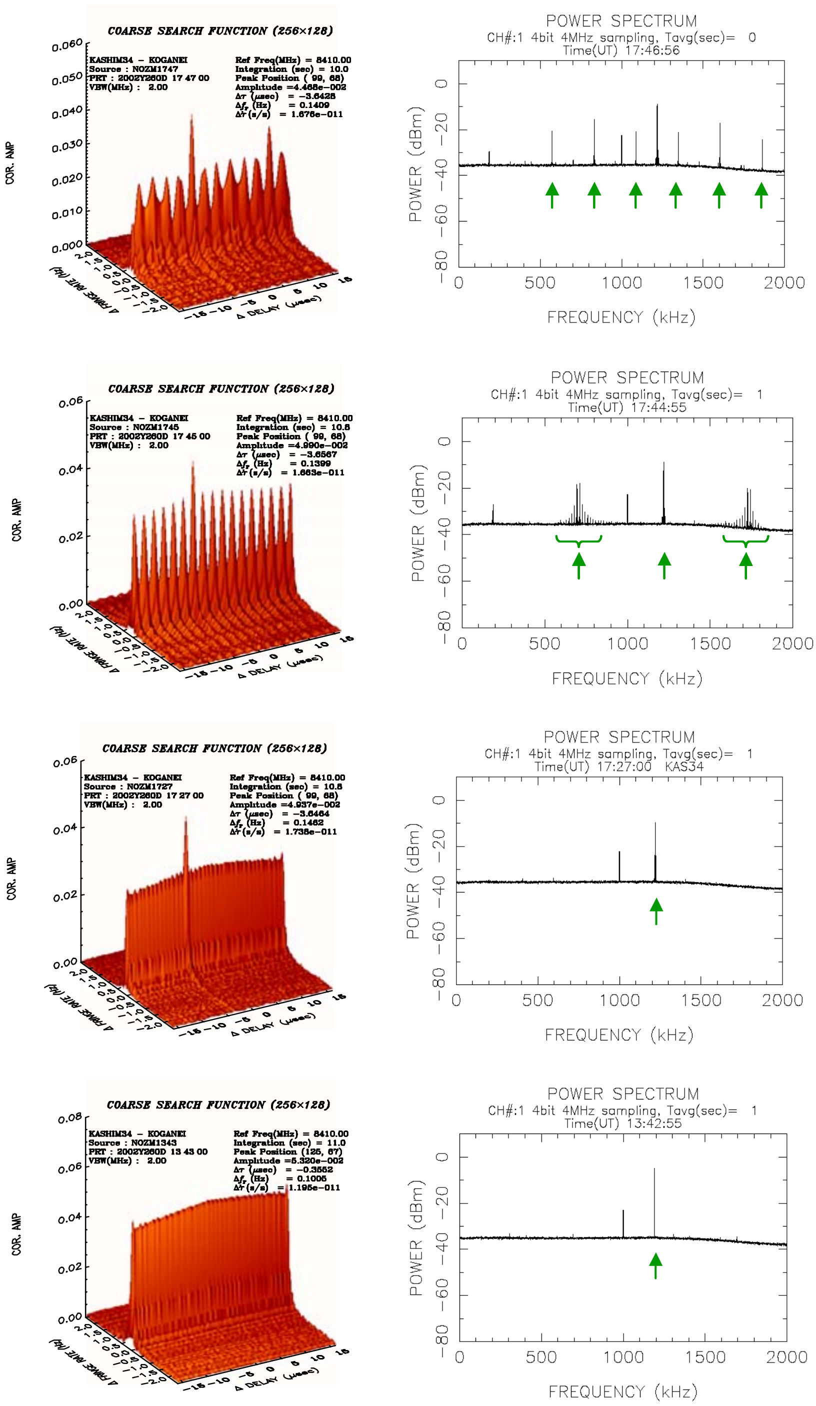

Fig.7. Fringes detected for NOZOMI. Group delays can be determined without ambiguity excepting the lowest panel case.

will remain. This is the idea of delta VLBI observation (e.g., Thornton and Border, 2003).

We have carried out a series of delta VLBI observations of GEOTAIL and NOZOMI using the K5-VSSP system since June, 2002 to learn characteristics of satellite downlink signals, to investigate the feasibility of delay measurements, and to utilize them for an actual orbit determination.

Two input-channels of a K5-VSSP are assigned for S and X band downlink signals. Observations are made with a sampling frequency of 4 MHz and an A/D resolution of either 4 bits or 2 bits. Observed data are FTPed to Kashima and are cross-correlated by PC. At present it is possible to obtain the delay time that is a VLBI observable to use for satellite positioning within a few days after observations. Fig. 5 shows the location of stations participated in the observations. Automatic observation control software

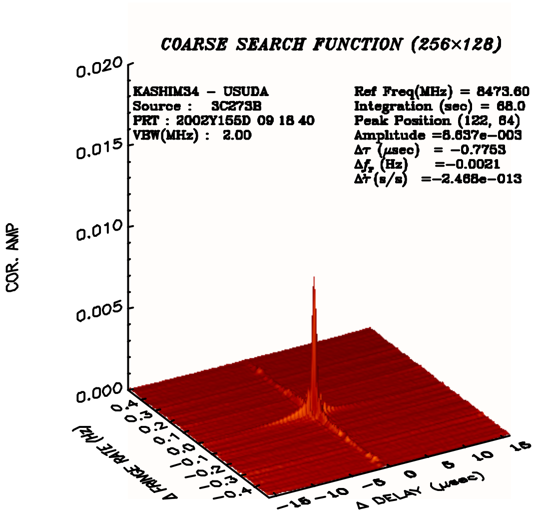

Fig.8. Fringe for QSO (3C273B).

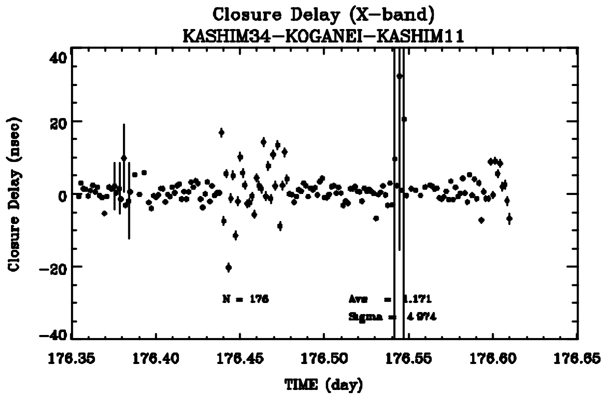

Fig.9 An example of closure delay test for GEOTAIL observations. Observations were carried out on June 25, 2002 at three stations, Kashima34, Kashima11, and Koganei11. Data with large error bars represent quasar observations. Although data are largely scattered around 176.45 days, standard deviation of total data is well less than 10 nsec.

was improved through a series of actual observations. Data reduction software was also developed and has been improved.

3.1 Fringes for different telemetry modes

In the differential one-way range (DOR) technique developed by JPL (Thornton and Border, 2003), telemetry signal is correlated with a computer generated model tone-signal to obtain the phase of each tone signal at each station. Then phases are differentiated between stations to get the cross correlation phase analogous to a quasar measurement. Delay is obtained as the slope of the phase versus frequency line. Unlike the DOR technique, we adopt the correlation processing as same as for a quasar processing, i.e., two station signals are directly correlated each other to obtain time delay. Thus the ordinary telemetry signal modulated by a complicated way is applicable for our delta VLBI observation. This increases the flexibility in a VLBI observation schedule because any special arrangement for telemetry mode is not necessary with a satellite control organization.

First we examined the possibility of group delay measurements by receiving telemetry signals. Then we investigated how the telemetry mode affects the delay measurements. Observed fringes (coarse delay search function) are summarized in Fig.6 for GEOTAIL and Fig.7 for NOZOMI with the spectrum of telemetry signals.

As shown in the figures, group delay can be obtained without ambiguities when telemetry signal is modulated with any data. However ambiguities appear when the telemetry mode is in the range measurement mode or non-modulated mode (lowest panels of Figs 6 and 7), because insufficient number of tones (or lack of continuum component) on the frequency domain results in multiple peak structures on the time domain. For comparison sake, an example of fringe for a quasar (3C273B) is shown in Fig 8. Narrower peak in delay domain compared with the case of telemetry signals reflects the difference in the spectrum broadness, i.e., quasar has wider spectrum than telemetry's. We made a closure delay test to evaluate the accuracy of observed group delays. In the case shown in Fig.9 a root mean square error of a few nanoseconds was attained with coarse delay measurements. Nanosecond accuracy is obtained for other cases and it seems to be a typical accuracy for our group delay measurements. Since this accuracy is ten times or more badly than the accuracy for quasar delay measurements (about 0.1nsec or better is easily achieved), the total positioning accuracy is strongly influenced by the error of spacecraft-delay measurements. An error of 1 nsec in spacecraft delay measurements on a 100 km baseline corresponds to an angle resolution of 3 μrad.

3.2 Fringe detection for extremely weak telemetry signals

The NOZOMI is the first Japanese Mars orbiter, and was launched on July 4, 1998. It was planned to arrive Mars in 1999 by using two-times lunar swing-bys and a powered earth swing-by. However due to malfunction of a thruster valve during the powered earth swing-by and maneuvers to recover the right trajectory to Mars, enough fuel is not left to inject NOZOMI into a Mars orbit. The NOZOMI team at ISAS

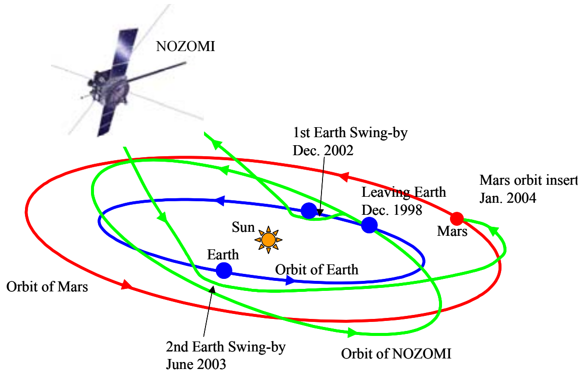

Fig.10. Trajectory of NOZOMI (after http://www.isas.ac.jp/e/enterp/missions/nozomi/traject.html)

found a new trajectory to Mars available to inject NOZOMI into a Mars orbit. Hence the orbit insertion scheduled in 1999 was abandoned, and it is now scheduled early in 2004 after two more earth swing-bys (Fig.10). During the two earth swing-bys telemetry signal intensity was supposed to become very weak due to the bad geometrical relation between spacecraft attitude and earth position, i.e., the high-gain antenna of NOZOMI does not point the Earth during this period. We carried out VLBI observations during this period to assess the sensitivity of our system and demonstrate the measurement accuracy if possible.

The NOZOMI moved to the high declination area after the first earth swing-by in December, 2002. Signal intensity became so weak from January to April, 2003 that integration time of 30 minutes or more was required to secure sufficient SNR. New fringe search software was hence developed to integrate the data over 30 minutes or more. An idea searching the acceleration of fringe rate was introduced into the new software to make possible to get fringes under insufficient a priori value. This new fringe search worked well as demonstrated in Fig 11.

4 Conclusions

We have carried out a series of delta-VLBI observations of GEOTAIL and NOZOMI using IP-VLBI system since June, 2002 to learn characteristics of satellite downlink signals and to investigate the feasibility of delay measurements. Results show that most of the cases we can determine group delays for telemetry signals with an accuracy of a few nanoseconds without any ambiguities. This accuracy will give an angle resolution of a few μrad on domestic baselines in Japan (about 100km or so), but it is insufficient resolution compared with a requirement of 0.5 μrad for NOZOMI navigation. Phase delay measurements under development will increase the measurement

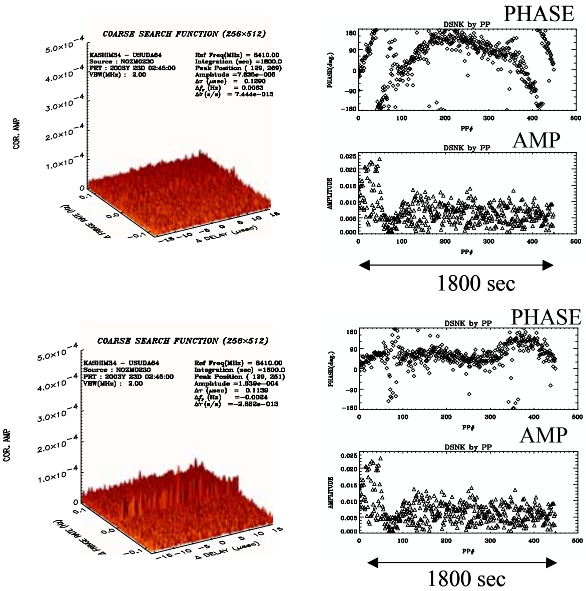

Fig.11. A normal fringe search for 30 minute scan data (upper two panels) and an improved fringe search (lower two panels).

accuracy by an order or more, but ambiguities must be solved for the orbital determination. We intend to develop orbital determination software that solves the ambiguity and the position simultaneously.

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