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Data processing center of RadioAstron space VLBI project

M.V. Shatskaya *, A.A. Abramov, N.A. Fedorov, V.I. Kostenko, S.F. Likhachev, S.I. Seliverstov, D.A. Sychev

Astro Space Center of Lebedev Physical Institute of RAS, 84/32 Profsoyuznaya st., Moscow, GSP-7 117997, Russia

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Abstract

In this paper, questions on development, implementation, and operation of RadioAstron project Data Processing Center (DPC) are reviewed. The main components of the dedicated DPC are the computer complex with 1 TFlops/s performance, storage with memory capacity of approximately 10 PB, the network infrastructure, and the corresponding communication channels. Performance enhancement methods and resolution of information storage, archiving, and process problems of space VLBI high-speed digital data flows are analyzed. It is shown that successful operation of DPC is mainly provided by optimal organization of computer system structure, storage, and networking transmission. Some of the important key features of RadioAstron project DPC and its comparative differences from the standard VLBI procedures are considered.

Keywords: VLBI; Data processing center; Radio interferometry; Storage systems; Data transferring; High-performance computing

1. Introduction

RadioAstron, a 10-meter radio telescope, was launched from the Baikonur Cosmodrome to the high-apogee near-Earth orbit on July 18, 2011. This project is a space-ground VLBI complex (very large baseline interferometer). It consists of a 10-meter space radio telescope "Spektr-R" and ground global VLBI network (Alexandrov et al., 2012).

The RadioAstron project was developed in Astro Space Center of PN Lebedev Physical Institute. (ASC LPI) (http://www.asc.rssi.ru/RadioAstron/eng/index.html) with the support and participation of Russian Space Agency.

The radio interferometric method assumes that several telescopes work together as a single large-phased radio telescope. The diameter of the phased telescope in this case will be equal to the distance between the participating radio telescopes. Such an approach allows to significantly increase the angular resolution of the instrument as compared to the single radio telescope. RadioAstron operates in the high-apogee near-Earth orbit together with ground radio telescopes, forming a radio telescope with a diameter of up to 350,000 km (see Fig. 1). The scientific goal of this project is to investigate different astrophysical objects: active galactic nuclei (AGN), quasars, masers using high angular resolution (up to 8 μas). One of the most important scientific goals in the RadioAstron project is the QSO brightness temperature measurement, which showed an excess of 10^{12} K limit imposed by synchrotron self-absorption (Kardashev et al., 2013). The results of scientific data correlation in the project yield the detection at baseline projections of up to 344,000 km.

The RadioAstron space-ground interferometer consists of a large number of ground radio telescopes. This number can vary from three to thirty telescopes depending on the scheduled observation. All these telescopes simultaneously record information. It is rather difficult to imagine the operation of such project without the involvement of

* Corresponding author.
E-mail address: mshatsk@asc.rssi.ru (M.V. Shatskaya).

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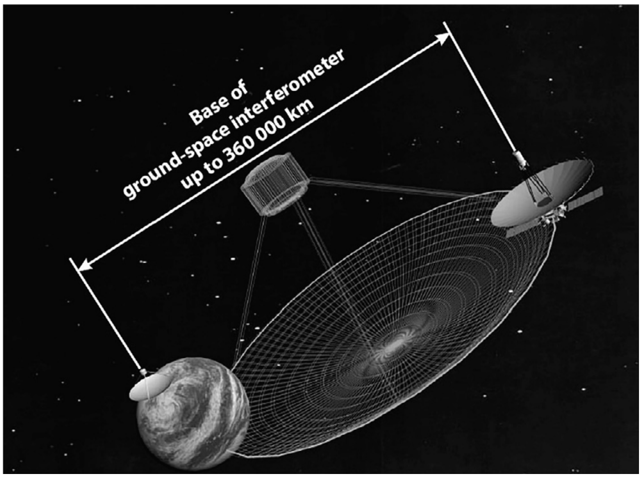

Fig. 1. Configuration of the RadioAstron space-ground interferometer.

modern computer technologies. Therefore, the implementation of the Data Processing Center (DPC) of the RadioAstron project is one of the main priorities.

Since the launch of RadioAstron, the DPC has grown significantly. Many factors led to the huge increase in scientific data volume (up to 800 TB per year):

– High interest by the global scientific community in the project.
– Increase in the duration of observing sessions.
– Launch of additional tracking station, located in the United States.
– Increased number of ground radio telescopes for making observations.

Thus, the data rate has increased together with computational and data analysis load. One cannot predict all the details of data processing in advance before the mission launch. Therefore, the DPC should be a dynamic, scalable system that follows the increasing needs of the project.

2. Systems for ensuring the operability and safety of the DPC

DPC is a centralized fail-safe system of interconnected software and hardware components.

The implementation of any data processing center begins with

– Facility room preparation.
– Organization of engineering infrastructure to ensure operability and safety.
– Power supply arrangement.
– Estimation of heat release and cooling capacity.

The DPC is equipped with a modern air conditioning and ventilation system with N + 1 configuration. In case of failure of one of the air conditioners, another one will automatically turn on. The DPC has a system of uninterruptible and stabilized power supply. Such system excludes the loss of data and equipment failure in case of power loss or voltage jump. Additionally, the server room of the data center has the monitoring and video control system. These systems allow to perform operational control of the data center equipment and to monitor the engineering systems in real time. All functions to manage engineering systems are available through the user interface. The server room also has a gas fire extinguishing system.

3. Tasks of the processing center: Rapid exchange of service information

RadioAstron DPC has a vast number of tasks (http://www.asc.rssi.ru/RadioAstron/documents/rmoh/eng/contents.htm).

These tasks are as follows:

– Collection, storage, and processing of raw scientific data. The data are a digital record of the signal received from the astronomical radio sources.
– Organization of service information exchange among the participants of the project. The data exchange between the ballistic center, the flight control center, RadioAstron observation scheduling center, ground tracking stations located in Pushchino (Russia) and Green Bank (USA), and ground radio telescopes is also organized through the DPC (see Fig. 2).

The scheme of data exchange is as follows:

– Ground tracking station located in Pushchino (Russia) or Green Bank (USA) receives the scientific data from the spacecraft at a rate of 144 Mbit/s through High Data Rate Communication (HDRC) radio link.
– Telemetry information, tracking station status report, and scientific data are transferred from the tracking station to DPC, located in Moscow. Telemetry is delivered from Pushchino to the DPC in real time by two ways. The first way is by transferring from the tracking station directly through a dedicated channel. The second one is transferring of telemetry through the flight control center. Such an approach increases the reliability of telemetry delivery.
– DPC also receives the information from Green Bank (USA) tracking station. The data format is similar to that for Pushchino. Information delivery is also performed through online mode.
– DPC accumulates the information on predicted and recovered orbits from the ballistic center.
– DPC receives telemetry data from control stations by tracking headquarters. DPC receives the data through online mode. Engineers of the processing center can monitor and analyze the status of onboard equipment using special software.

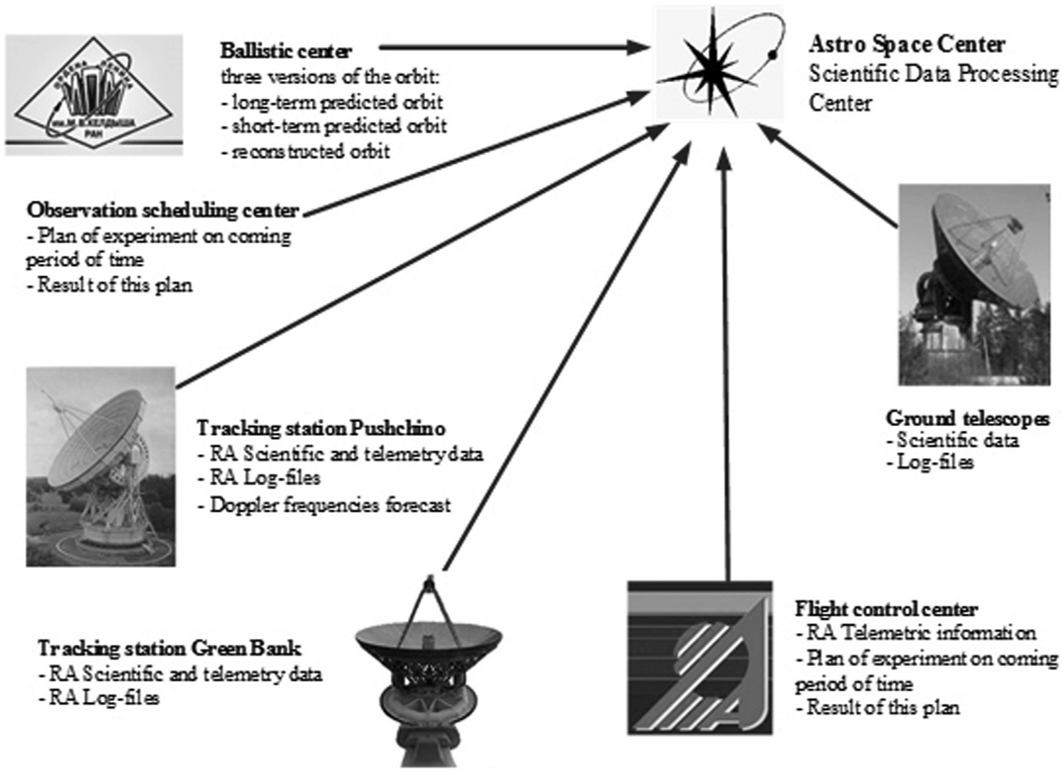

Fig. 2. Scheme of information exchange in the RadioAstron project.

– There is intensive data traffic between the observations planning group, the tracking headquarters, and ground radio telescopes through DPC.
– Ground radio telescopes transfer the log files of scientific observation sessions and the corresponding scientific data to the DPC.

All the information is important for the effective operation of the project, control of onboard equipment, and processing of raw scientific data. For convenient access to the service information, a dedicated web interface was developed.

Additionally, an online database was organized to systematize the information on data transferring, processing, and archiving.

It should be noted that service information as compared to the scientific data has smaller volume – <4 TB in total for seven years of mission operation.

4. Scientific data transfer from tracking stations and ground radio telescopes: Data storage procedures

In addition to the space radio telescope, the DPC collects information from all ground radio telescopes that participate in joint observations with RadioAstron. Approximately 10 antennas participate in the observations immediately after the launch. However, because of the huge interest in the RadioAstron project worldwide, the number of radio telescopes taking part in the joint observations is growing rapidly. Presently, ground support includes up to 60 telescopes (see Table 1).

Data recording rate for a single radio telescope can vary from 256 Mbps to 2048 Mbps in different experiments. The volume of scientific data, received from a single ground radio telescope, can range from 100 GB to 800 GB for 1 h of observation.

RadioAstron performs the observations together with the radio telescopes from 23 countries: Europe, Asia, Australia, Africa, and North America. Table 1 lists all ground telescopes. RadioAstron observes together with approximately 60 ground telescopes. Statistics of ground radio telescope participation in the observations are shown in Fig. 3. These radiotelescopes take part in more than 300 observations.

More than 100 TB scientific data were collected for the first year of observations (fringe search stage of the mission), and approximately 300 TB data were collected for the second year of the mission (early science program). The third year of observations was the first year of a key science program. Requests for observations came from 14 international scientific groups, which implied approximately 4000 h of observations of the space radio telescope. The decision to expand the DPC of the RadioAstron project was made. The amount of data downloaded to the storage since the beginning of regular observations of the key science program (summer 2013) reached 800 TB per year.

All scientific data are collected in the repository. This is one of the features of the RadioAstron project. Presently,

Table 1
List of ground radio telescopes.

Telescope code	Telescope name	Telescope diameter	Country
Ak	ASKAP (Australian SKA Pathfinder telescope)	12 m	Australia
Ar	Arecibo	305 m	Puerto Rico
At	ATCA	6 * 22 m	Australia
Bd	Badary	32 m	Russia
Br	Brewster	25 m	USA
Cd	Ceduna	30 m	Australia
Ef = Eb	Effelsberg	100 m	Germany
Ev	Evpatory	70 m	Ukraine (before march 2014)
Fd	Fort Davis	25 m	USA
Gb	Green Bank	100 m	USA
Hh	Hartebeesthoek	26 m	South Africa
Hn	Hancock	25 m	USA
Ho	Hobart	26 m	Australia
Ib	Irbene	16 m	Latvia
Ir	Irbene	32 m	Latvia
Jb = Jb1	Jodrell Bank, Lovell	76 m	Great Britain
Jb2	Jodrell Bank	38 m * 25 m	Great Britain
Kl = Kz	Kalyazin	64 m	Russia
Km	Kunming (40 m)	40 m	China
Kp	Kitt Peak (VLBA antenna)	25 m	USA
Ks	Kashima (34 m)	34 m	Japan
Kt	KVN Tamna	21 m	Korea
Ku	KVN Ulsan	21 m	Korea
Ky	KVN Yonsei	21 m	Korea
La	Los Alamos (VLBA antenna)	25 m	USA
Mc	Medicina	32 m	Italy
Mh	Metsahovi	14 m	Finland
Mk	Mauna Kea (VLBA antenna)	25 m	USA
Mp	Mopra (LBA)	22 m	Australia
Nl	North Liberty (VLBA antenna)	25 m	USA
Nt	Noto	32 m	Italy
O6 = On20 = On60	Onsala	20 m	Swedish
O8 = On25 = On85	Onsala	25 m	Swedish
Ooty	Ooty Radio Telescope	534 m * 30 m	India
Ov	Owens Valley	25 m	USA
Pa	Parks	64 m	Australia
Pt	Pie Town	25 m	USA
Ro70	Robledo	70 m	Spain
Sc	Saint Croix	25 m	USA
Sh	Sheshan	25 m	China
Sm = Sz	Simeiz	22 m	Russia
Sr	Sardinia	65 m	Italy
Sv	Svetloe	32 m	Russia
Td = Ti	Tidbinbilla	70 m	Australia
Tm = Tm65 = T6	Tianma	65 m	China
Tr	Torun	32 m	Poland
Ud = Us	Usuda	64 m	Japan
Ur	Urumqi	25 m	China
Wa	Warkworth	30 m	New Zealand
Wb	Westerbork (array)	25 m * 14	The Netherlands
Wb1	Westerbork (1 telescope)	25 m	The Netherlands
Wn	Wettzell	13 m	Germany
Ww	Warkworth	12 m	New Zealand
Wz	Wettzell	20	Germany
Y = Y27	VLA	25 m * 27	USA
Ys	Yebes	40 m	Spain
Zc	Zelenchukskaya	32 m	Russia

the total amount of collected data in DPC is approximately 3500 TB.

Usually, the primary data (so-called “raw” data) in VLBI observations are usually deleted because of their huge volume. The usual practice is that only the correlation results are stored. In this case, there is no possibility to perform further data reprocessing. Luckily, the additional optimization of data processing and storage allowed us

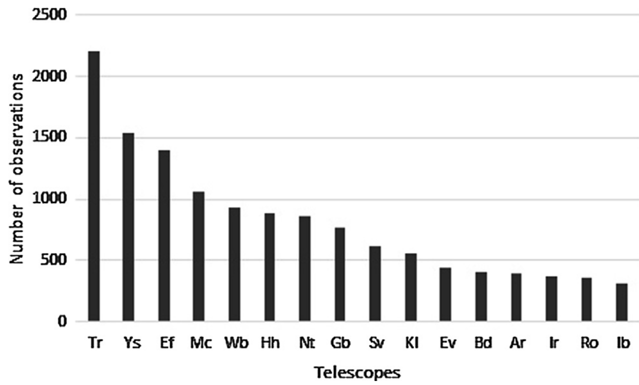

Fig. 3. Statistics of ground radio telescopes participation in observations.

to find a way to multiply resources for a global archiving procedure for all incoming data of the RadioAstron project. Storage of all the raw data of the RadioAstron project provides the researchers an opportunity to reprocess the data, improve the processing methods, and effectively evaluate new scientific results.

Storage of all project data is justified. Presently, the data of the projects are reprocessed with a new, more accurate version of the orbit. Consequently, a correlation was obtained in additional 7% of the experiments.

The data storage of the RadioAstron project consists of two parts: online and offline storage systems. The total capacity of online storage is currently approximately 800 TB and that of offline storage is approximately 9000 TB.

We pay special attention to the storage reliability. We use RAID 6 technology for online storage. RAID 6 has the highest level of reliability. This technology suggests usage of the sets of hard disks, which are available to users as one logical drive. The disk array contains additional capacity to enable data recovery in case of malfunction.

Reliable storage requires at least two copies of information in different rooms. The offline storage is divided into two parts: one copy of all data is stored on hard disks (4500 TB) and another copy on magnetic tapes (4500 TB). The tape library is used for recording the data on magnetic tapes. The library has the ability to create blocks of several tapes to perform the hot-swap of tapes (1.5 TB capacity) using load/unload cartridge stores.

Each type of storage hard disks and tapes has its pros and cons. Hard drives are less reliable in terms of mechanical effects, but they are faster, more common, and convenient. It makes their usage simple and affordable. Storage of information on tapes is much more reliable. Manufacturers of magnetic tapes guarantee the lifetime of tape cartridges to be not less than 30 years. It is recommended to use tape storage for long-term storage. However, tape library requires uncommon equipment to perform data reading and writing. Thus, usage of magnetic tape is less convenient.

The number of observing sessions is large, which exceeds 100 observations per month in the winter season when there are no restrictions for the spacecraft, caused by the Sun. For convenience, information of the delivery status of the data from telescopes, as well as the archiving and processing status, is provided on the internal online database.

5. Composition and structure of the DPC

Initially, DPC consisted of the main server, 10 nodes with 100 CPU cores in total, that is, 200 TB data storage system, and network switches (see Fig. 4). All equipment was connected through the 10 GBit/s network. The performance of the organized computing cluster, calculated by the Linpack program, is 1 Tflop/s.

Servers are connected to each other by two networks. One of the networks is private to exchange the MPI traffic, and it has a bandwidth of 10 Gbit/s. The second network is public, and it uses the Gigabit Ethernet interface to manage the servers, store data, and access the cluster servers through the remote desktop.

Initially, data storage was organized as DAS (Direct Attached Storage), which was connected directly to the head server. Its volume was approximately 200 TB. Data were collected in this repository. Data processing was performed on a cluster with 10 server nodes using this DAS.

During the DPC operations, some problems emerged. These problems slowed down the process of delivery, verification, processing, and archiving of the data. One of the bottlenecks was the main server and DAS. Multiple procedures of reading and writing on the storage through the head server interrupted each other. We had to optimize the structure of the DPC (Shatskaya et al., 2012).

DPC was repeatedly transformed and expanded during mission operation. Therefore, the final configuration was implemented (see Fig. 5).

The present processing center includes

- Online storage system for collecting information – 450 TB.
- Online storage system for data processing – 85 TB.
- Online storage system for processing results – 310 TB.
- Hard drive archive data storage – 4500 TB.
- Tape archive data storage – 4500 TB.
- Backup storage of 20 TB, located in Pushchino.
- The total storage capacity is approximately 10 PB.
- Computer system with performance of 1 TFlop/s.
- 1 Gbit/s and 10 Gbit/s network channels.
- 800 Mbit/s Internet channel.

The processes of collecting, verifying, processing, and archiving of the data are separate. The special online storage system with capacity of 450 TB is used to collect and check the data of the observation sessions. After that, the data are recorded on the hard disks and magnetic tapes into offline storage. Any data manipulation is accompanied by the verification of its checksums. It is important to guarantee not only the data delivery but also the reliability of

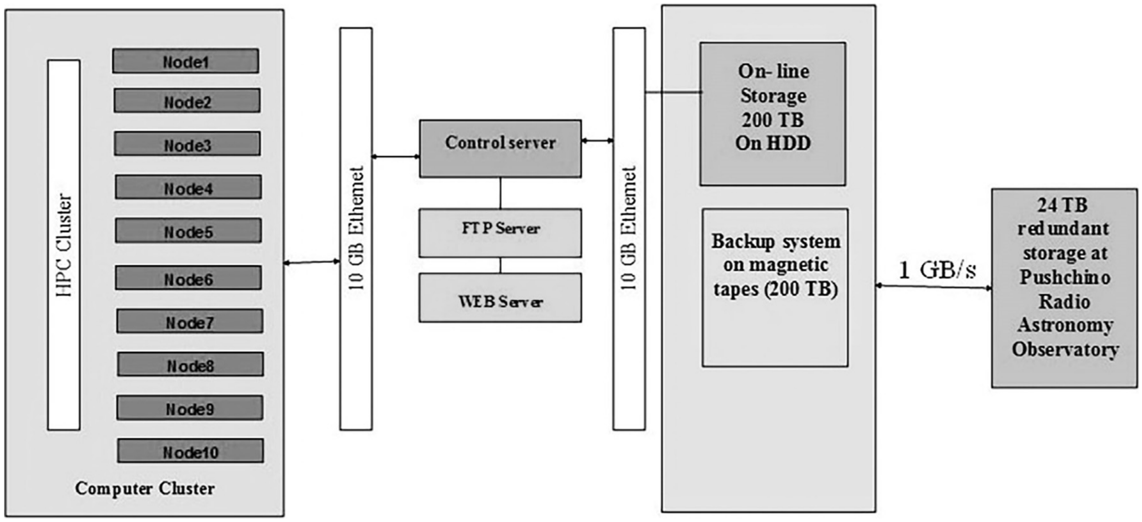

Fig. 4. Scheme of computer complex and storage operation.

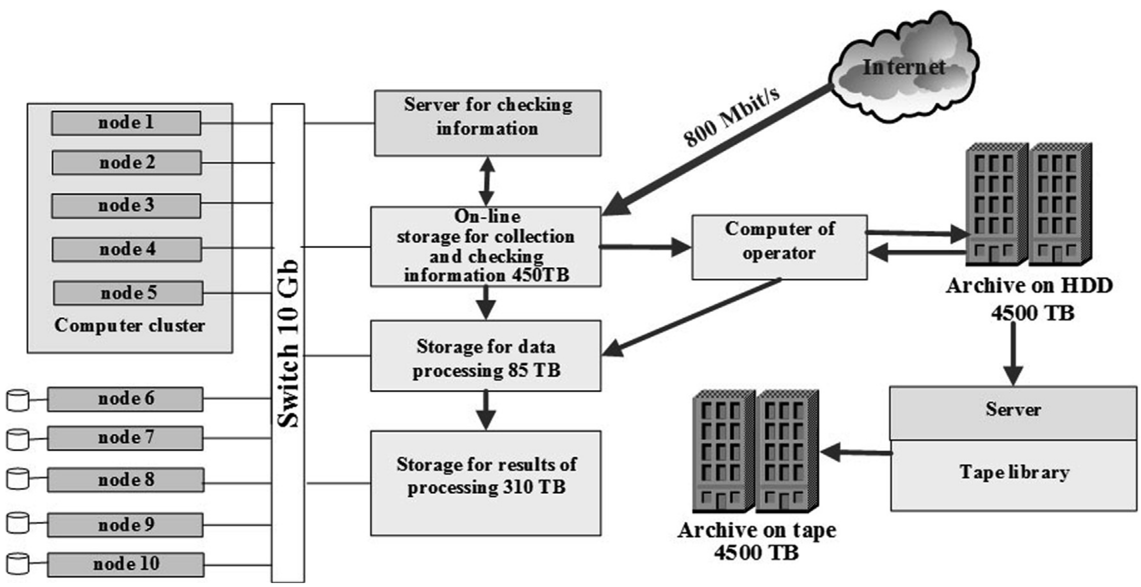

Fig. 5. Computer complex and data storage operation diagram.

data storage. Data are put to the special storage for processing according to the corresponding requests. This storage has a capacity of 85 TB. A separate storage system has been allocated for the correlation results. It is repeatedly extended. Presently, its volume is approximately 310 TB, and it is accessible from the Internet. Thus, the organized scheme of DPC increased the processing speed of raw scientific data.

To avoid the bottlenecks related to the main server, we had to stop using the DAS. Currently, Network Attached Storages (NAS) are used. Fault tolerance of the storage system is achieved by the usage of two redundant hot-plug power supplies.

A cluster with ten nodes was replaced with the five-node cluster to optimize the performance. The remaining five nodes are used as separate computational nodes for the correlation (Likhachev et al., 2017).

6. Network infrastructure of DPC

The transfer of a large amount of raw scientific data across significant distances, as well as the delivery of service information in the online mode, requires high-speed communication channels. Fig. 6 shows the scheme of DPC communication channels.

To deliver of telemetry from the tracking station (Pushchino) and from the tracking headquarter to the DPC, special optical communication lines between DPC (Moscow), tracking headquarter, and the tracking station in Pushchino were established. A dedicated channel with a capacity of 1 Gbit/s between the tracking station in Pushchino and DPC was organized. The channel is used to perform the express delivery of raw scientific data. Switching equipment was chosen to provide the necessary bandwidth of communication channels and reliability of information

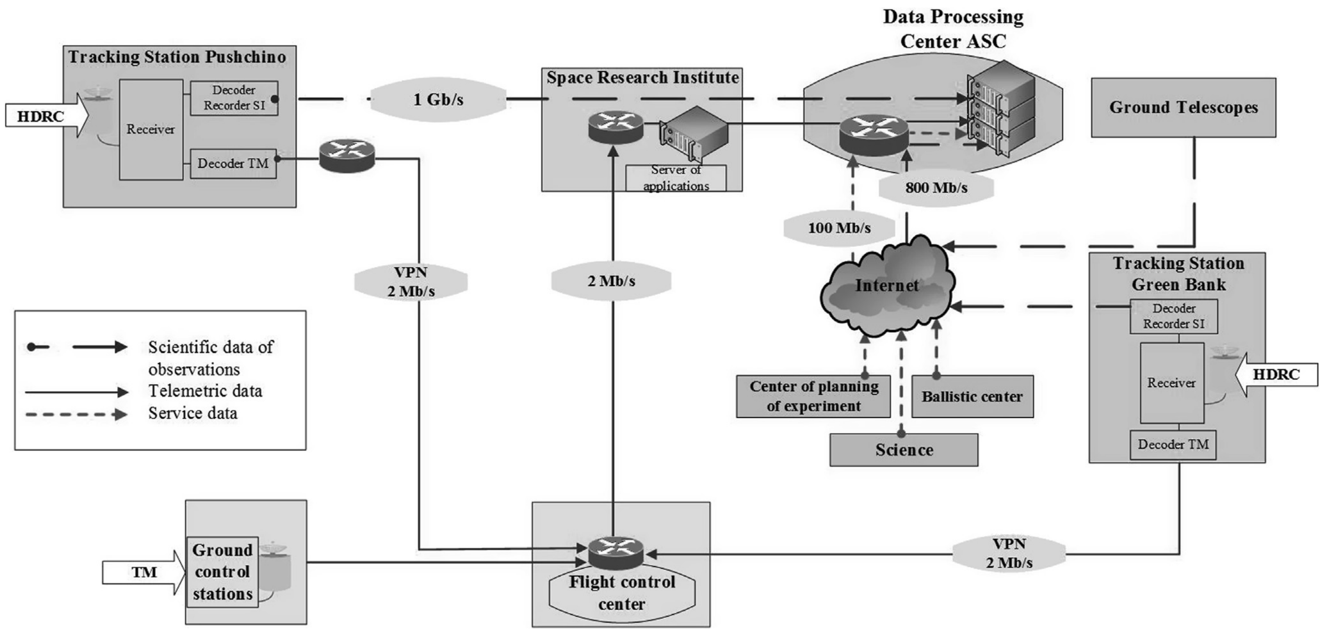

Fig. 6. Data Processing Center communication channels (SI – scientific information, TM – telemetry information, HDRC – High Data Rate Communication radio link).

transfer across significant distances. Additional testing of optical lines confirmed these conclusions.

For administrative and logistical reasons, RadioAstron raw data from ground tracking stations (Pushchino and Green Bank) as well as all involved in observations ground-based radio telescope arrive to the Astro Space Center DPC through the publicly available Internet. This approach is different from the widely used e-VLBI practice, for example, the EVN, which involves the GEANT network. In some cases, the delivery of scientific data requires several "connections" at intermediate data handling centers, for example, at the MPIfR in Bonn, Germany, or JIVE, in Dwingeloo, the Netherlands.

The standard FTP is used to receive the scientific raw data. The data transmission system actively uses multithreading, which significantly increases the transfer rate. In addition to transferring the imaging sessions data from distant telescopes, we use the TSUNAMI protocol, which unites the advantages of UDP and TCP protocols. The main peculiarity of imaging sessions is the huge volume of data. Up to 30 ground telescopes can participate in a single imaging observation, and typical bit rate in these sessions can be up to 2 Gbit/s. The total volume of such single observation can be up to 100 TB. Transferring of the imaging sessions data across the Internet is nontrivial and could be challenging.

An Internet channel with 800 Mbit/s was organized to receive the raw scientific data. Most of the telescopes transmit the data relatively quick. It takes from three days to a month to receive the data from the telescopes. However, owing to the large number of sessions, human factor (errors), lack of high-speed communication channels at some telescopes, and other reasons, the time of delivery of the observations can increase up to 5–6 months.

The speed of data transfer in RadioAstron mission is limited not only by a bottleneck at the DPC but also by the current quality of Internet connection in general and the transmission channel of a specific telescope in particular. The speed of data transfer from a particular telescope depends on the time of the day, the day of week, and other conditions and can fluctuate in a wide range.

The data are delivered on disks from places where high-speed communication channels are not available. The tracking station in Green Bank uses such an approach. First, the data are delivered on disks to Charlottesville (USA), and thenr they are sent through the Internet to the DPC. The processing of data delivery in Green Bank was optimized; therefore, currently, the delay in the data receiving from Green Bank is approximately 1–2 days.

The distributed network infrastructure provides the possibility of high-speed data exchange in the RadioAstron project and meets the mission requirements for the DPC.

7. Conclusions

Currently, the DPC of the RadioAstron project is a high-tech dynamic system, which has been successfully under operation for 7 years and is involved in collecting, processing, and storing of project information. DPC has undergone significant changes during the operation of RadioAstron mission. Operation of the DPC of the RadioAstron project is different from that of the standard VLBI scheme in terms of the delivery and storage of big data volumes. Presently, the DPC has an unique archive of all scientific observations of the mission.

Implemented functionality of the DPC allows to perform effective data collection, storage, and processing with the required reliability and speed.

The experience, scientific, and technical solutions implemented in the DPC for the RadioAstron project will be used in the development of the DPC for the next-generation space VLBI project – "Millimetron" (http://millimetron.ru).

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