Oral Presentation Abstracts

Tuesday, January 28, 2020

Tuesday, January 28, 2020			
7:30 AM	9:00 AM	Registration	
8:45 AM	9:00 AM	Welcome	
		Science Motivation	**Session Chair: Heino Falcke**
9:00 AM	9:40 AM	The Future of High-Resolution Radio Interferometry in Space	L. Gurvits & V. Fish
9:40 AM	10:00 AM	Mapping Spacetimes with Horizon-scale Imaging	A. Broderick
10:00 AM	10:20 AM	The Sharpest View of Blazar Jets with Space VLBI	J. Gomez
10:20 AM	10:50 AM	Break	
10:50 AM	11:30 AM	Ergomagnetospheres, Ejection Disks and Relativistic Jets	R. Blandford
11:30 AM	11:50 AM	Black Hole Science with Extremely Long Baseline Interferometry	D. Pesce
11:50 AM	12:10 PM	Measuring Black Hole Spin with Time-domain VLBI Observations of Infalling Gas Clouds	K. Moriyama
12:10 PM	12:30 PM	Multi-messenger Astronomy with Space mm VLBI	V. Ravi
12:30 PM	2:00 PM	Lunch (90 min)	
		Science Motivation con't	**Session Chair: Anton Zensus**
2:00 PM	2:20 PM	Simulations of VLBI Observations of Black Holes and Jets from Space	F. Roelofs
2:20 PM	2:40 PM	Polarization Imaging of M87 Jets by General Relativistic Radiative Transfer Calculation Based On GRMHD Simulations	Y. Tsunetoe
2:40 PM	3:00 PM	The Need of Space VLBI for the Space Geodesy Program	L. Petrov
3:00 PM	3:40 PM	Discussion Topic: Space vs. Ground	
3:40 PM	4:10 PM	Break	
4:10 PM	4:50 PM	VSOP-1 (HALCA) Project	Y. Murata
4:50 PM	5:30 PM	The Space VLBI Mission RadioAstron: Overview and Results	Y. Kovalev
5:30 PM	5:35 PM	Poster Flash (5 min)	
5:35 PM	6:35 PM	Reception	

Vincent Fish (MIT Haystack Observatory)

Leonid Gurvits (JIVE)

Topic: Science Goals

The Future of High-Resolution Radio Interferometry in Space

Radio astronomy has not reached yet the saturation level in terms of angular resolution. In all frequency domains, from ultra-low frequencies below the ionosphere cut-off of about 10 MHz to sub-millimeter wavelengths (frequencies up to and beyond 1 THz), science cases requiring presently unavailable angular resolutions are strong. These requirements can be met only by space-based radio telescopes. At ultra-low frequencies, the telescope (interferometer) must be outside the Earth's ionosphere screen. At meter to millimeter wavelengths, Earth-based VLBI systems operate at the longest baselines, comparable with the Earth diameter, and their resolution is not sufficient for many scientific applications. Finally, at short millimeter and sub-millimeter wavelengths, the atmosphere is opaque. The EHT system operates near the practical limit of angular resolution for Earth-based interferometers.

Three implemented to date Earth-Space VLBI systems, TDRSS (1986–1988), VSOP/HALCA (1997–2003), and RadioAstron/Spekr-R (2011–2019) demonstrated the feasibility of interferometry with baselines longer than the Earth diameter. Importantly, they also define ‘starting points’ for a number of key technology developments required by prospective Earth-Space and Space-Space radio interferometers. In this presentation we review major technology requirements for a space-borne radio interferometer as defined by the current astrophysical agenda. In particular, we briefly overview several trade-offs which must be addressed in the design studies of prospective high resolution space-borne interferometers. These encompass the specific radio astronomy instrumentation (antenna, analogue and digital backends, data transport and processing, local oscillators, etc.) as well as service sub-systems of spacecraft. In this presentation we consider specifications and main technical requirements for a hypothetical space-borne sub-millimeter interferometer able to push further the envelope currently defined by the EHT.

Avery Broderick (Perimeter Institute/University of Waterloo)

Topic: Science Goals

Mapping Spacetimes with Horizon-scale Imaging

The Event Horizon Telescope has opened a new window onto spatially and temporally resolved studies of near-horizon phenomena about supermassive black holes. Images, and more importantly, movies of transient features provide a unique opportunity to probe general relativity. With such events, it is possible to tomographically map black hole spacetimes, resulting in high-precision tests of the nature of black holes and the mechanisms by which they interact with the matter about them. I will describe how such experiments may be done with the existing EHT capabilities and the utility of being able to repeat these measurements for large populations of such objects in the future.

Jose Gomez (Instituto de Astrofisica de Andalucia - CSIC)

Andrei Lobanov (Max-Planck-Institut fur Radioastronomie)
Gabriele Bruni (Istituto di Astrofisica e Planetologia Spaziale)
Yuri Kovalev (Lebedev Physical Institute)
Antonio Fuentes (Instituto de Astrofisica de Andalucia - CSIC)
Evgeniya Kravchenko (INAF Istituto di Radioastronomia)

Topic: Science Goals

The Sharpest View of Blazar Jets with Space VLBI

Investigating how blazar jets are launched, and what is the role of the magnetic field in the jet dynamics, emissions, and actual jet formation requires probing these sources at the highest angular resolutions. Over the past decades two space VLBI missions, VSOP in the late 90's and more recently RadioAstron, have provided the sharpest view of blazar jets. With a perigee height of about 350,000 Km, RadioAstron has allowed imaging some of the most powerful blazar jets at unprecedented angular resolutions of the order of few tens of microarcseconds, paving the way towards the next generation of space VLBI missions. We summarize the results of our RadioAstron "Polarization" Key Science Program, which has run for the entire duration of the Space VLBI missions and accounts for about 70% of all the imaging experiments conducted, probing the magnetic field and innermost jet regions in a sample of the brightest blazars.

Roger Blandford (KIPAC, Stanford)

Topic: Previous Space Missions

Black Hole Ergomagnetospheres, Electromagnetic Jets and Ejection Disks

Recent, remarkable images made by the EHT collaboration of M87 exhibit a ring of emission, presumably orbiting a six billion solar mass black hole. It is proposed that what is observed is not an ion pressure-supported torus, but an extensive ? ergomagnetosphere" that connects mechanically to a much larger ``ejection disk??, through a "magnetic clutch?. It is conjectured that this magnetic clutch sustains instabilities that transport energy and angular momentum outward as well as upward. The ejection disk is envisaged to be powered primarily by the spinning hole and not the infalling gas, which is all expelled as a jet-confining, hydromagnetic wind. Implications for general active galactic nuclei, other sources of relativistic jets and future Space VLBI observations will be briefly discussed.

Dominic Pesce (Center for Astrophysics | Harvard & Smithsonian)

Kari Haworth (Center for Astrophysics | Harvard & Smithsonian)
Gary Melnick (Center for Astrophysics | Harvard & Smithsonian)
Lindy Blackburn (Center for Astrophysics | Harvard & Smithsonian)
Maciek Wielgus (Center for Astrophysics | Harvard & Smithsonian)
Alexander Raymond (Center for Astrophysics | Harvard & Smithsonian)

Topic: Science Goals, Synergies with other Instruments

Black Hole Science with Extremely Long Baseline Interferometry

Situated 1.5 million km from the Earth, a radio telescope located at the Sun-Earth L2 Lagrange point could function as a uniquely valuable node in a VLBI network. The unprecedented angular resolution resulting from the combination of a station at L2 with existing ground-based submillimeter/millimeter telescopes would increase the number of spatially resolvable black holes by as much as a factor of a million, permit the study of these black holes across all of cosmic history, and enable new tests of General Relativity by unveiling the photon ring substructure in the nearest black holes. Both the Origins Space Telescope and the Millimetron Space Observatory are proposed missions that could feasibly accomplish these science goals.

Kotaro Moriyama (Massachusetts Institute of Technology Haystack Observatory)

Shin Mineshige (Kyoto University)
Mareki Honma (National Astronomy Observatory of Japan)
Kazunori Akiyama (NRAO / MIT Haystack Observatory)

Topic: Science Goals

Measuring Black Hole Spin with Time-domain VLBI Observations of Infalling Gas Clouds

Black holes are among the most important objects for testing general relativity. The black hole spacetime is described by two quantities: the black hole mass and spin. The mass can often be accurately estimated from astrometric observations of orbiting stars around the central black hole. Measuring the black hole spin requires information from the vicinity of the event horizon, which is spatially resolved for the Galactic center Sagittarius A* (Sgr A*) and nearby radio galaxy M 87 by means of very long baseline interferometry (VLBI) observations with the Event Horizon Telescope (EHT). However, it is not easy to extract the spin information from the horizon-scale emission, which depends on complexities of accretion flow properties and spacetime effects.

In this presentation, we simulate EHT observations of a gas cloud falling onto a black hole, and construct a method for spin measurement based on its relativistic flux variation. We investigate the signature of the spin dependency of relativistic flux variation by calculating the motion of an infalling gas cloud and photon trajectories in the Kerr spacetime using general relativistic ray tracing. The light curve of the infalling gas cloud is composed of peaks formed by photons which directly reach a distant observer and by secondary ones reaching the observer after more than one rotation around the black hole. The time interval between the peaks is determined by the period of photon rotation near the photon circular orbit, which uniquely depends on the spin.

We perform synthetic EHT observations of Sgr A* under a more realistic situation in which a number of gas clouds intermittently fall towards the black hole with various initial parameters. Even for this case, the signature of the black hole spin is detectable in correlated flux densities which are accurately calibrated by baselines between sites with more than one EHT observatory, such as Mauna Kea and Chajnantor. The synthetic observations indicate that our methodology can be applied to EHT observations of Sgr A* since April 2017. Importantly, horizon-scale movies of infalling gas clouds can be obtained by expanding the EHT ground array, providing a reliable measurement of the spin that is independent of the detailed properties of the accretion flow.

Vikram Ravi (Caltech)

Topic: Science Goals

Multi-messenger Astronomy with Space mm VLBI

Supermassive black holes (SMBHs) are expected to undergo up to a few major mergers with other SMBHs over a Hubble time, with the ultimate coalescences driven by the emission of gravitational waves (GWs). The next generation of millisecond pulsar timing-array experiments, enabled by the SKA, the DSA-2000, and the ngVLA, will be sensitive to GWs from merging binary SMBHs with masses of 10^9 solar masses within several hundred Mpc. However, substantial theoretical uncertainty exists regarding the lifetimes of binary SMBHs prior to GW-driven coalescence, and the effects of binary dynamics on jet launching and on the surrounding gaseous environments. Thus, synergies abound between GW observations and sensitive, high angular resolution observations of jets and accretion flows enabled by space mm VLBI. I will outline these synergies, and identify the resulting requirements for space-VLBI concepts.

Freek Roelofs (Radboud University)

Topic: Science Goals, New Mission Concepts

Simulations of VLBI Observations of Black Holes and Jets from Space

In this talk, I will discuss the imaging prospects of a new Space VLBI mission concept called the Event Horizon Imager (EHI). The EHI design consists of two or three satellites in Medium-Earth Orbits with slightly different radii, resulting in a dense spiral-shaped uv-coverage with long baselines, suitable for high-resolution and high-fidelity imaging of radio sources. We simulate observations of general relativistic magnetohydrodynamics models of Sgr A* and M87 with this configuration, with noise calculated from preliminary system parameters. Images of Sgr A* and M87 with a resolution of up to 4 uas could be reconstructed, allowing for stronger tests of general relativity and accretion models than with ground-based VLBI. Additionally, simulations of lower-frequency observations of other AGN show that the EHI could resolve the transversal jet structure, informing models of jet formation and collimation.

Yuh Tsunetoe (Kyoto University)

Shin Mineshige (Kyoto University)
Ken Ohsuga (University of Tsukuba)
Tomohisa Kawashima (NAOJ)
Kazunori Akiyama (NRAO / MIT Haystack Observatory)

Topic: Science Goals

Polarization Imaging of M87 Jets by General Relativistic Radiative Transfer Calculation Based On GRMHD Simulations

The spectacular images of the M87 black hole taken by the Event Horizon Telescope (EHT) have opened a new era of black hole research. One of the next issues is to take polarization images around the central black hole (BH). Since radio emission is produced by synchrotron process, polarization properties should vividly reflect the magnetic field structures at the jet base and thus provide good information regarding the magnetic mechanism of jet formation. With this kept in mind we perform general relativistic (GR) radiative transfer calculations of polarized light based on the GR magnetohydrodynamic (MHD) simulation data of accretion flow and outflow in M87, to obtain their linear and circular polarization images in the BH horizon-scale. We found that the linear polarization components originating from the jet base and inner accretion flow should experience Faraday rotation and depolarization when passing through magnetized plasmas around the BH, thus sensitively depending on the BH spin. Through the comparison with total intensity image at 1.3mm by the EHT and the polarization degree and the rotation measure (RM) measured at 1.3mm with the Submillimeter Array, the model with the spin parameter of a=0.9M_BH (with M_BH being the BH mass) is favored over other models with a = 0.5 M_BH or 0.99 M_BH, though we need further systematic studies for confirmation. We also find in low-temperature models clear ring-like image in the circular polarization map, which arises because of Faraday conversion of the linearly polarized synchrotron emission and is thus indicative of magnetic field direction. This occurs only when the emission region is threaded with well-ordered magnetic fields and hence no clear images are expected in high-temperature disk models, in which disk emission is appreciable. We will be able to elucidate the field configuration through the comparison between the simulated polarization images and future polarimetry with EHT and other VLBI observations.

Leonid Petrov (NASA GSFC)

Tuomas Savolainen (Aalto University Metsahovi Radio Observatory, Finland))

Topic: Science Goals

The Need of Space VLBI for the Space Geodesy Program

VLBI astrometry is able to measure source positions with an accuracy down to 5-10% of the beam size. The contribution to the group delay from the source structure at scales greater than the beam size can be accounted for by using a source image generated from the same observation. The contribution of source structure at scales less thana certain, signal-to-noise-ratio dependent, fraction of the beam size cannot be recovered from such images, and, when unaccounted, causes noticeable systematic errors that affect astrometry, space navigation, and geodesy. Discovery of sub-structure of the core regions at scales less than the resolution of ground-base interferometers made by the RadioAstron mission demonstrates that such an effect is real. We discuss how space VLBI can help to mitigate it.

Yasuhiro Murata (JAXA)

Topic: Other

VSOP-1 (HALCA) Project

VSOP-1 project was approved in 1989 in Japan, and the HALCA satellite was launched in 1997. It made space VLBI observation from 1997 to 2003 with huge helps from the international collaboraters. The HALCA satellite has about 8 m meshed surface antenna, with the orbit of perigee of 560km high and apogee of about 25,000km high. It had L band, C-band and Ka-band receivers, but we cannot observe Ka band because of large loss of feed. We will report the VSOP-1 project, how the project was carried out, and what was good and what was bad. We planned VSOP-2 project with following to the VSOP-1 project, but it was failed. We have many lessons and learned from those projects. We will report those and items we need to consider for future space VLBI project.

Yuri Kovalev (Lebedev Physical Institute)

Topic: Previous Space Missions

The Space VLBI Mission RadioAstron: Overview and Results

The RadioAstron Space VLBI mission utilized the 10-m radio telescope on board the dedicated Spektr-R spacecraft to observe cosmic radio sources with an unprecedented angular resolution at 92, 18, 6 and 1.3 cm in total and polarized light. The longest baseline of the space-ground interferometer was about 350 000 km. It operated in 2011-2019 together with 58 largest ground radio telescopes. Resolution as high as 8 and 11 µas has been achieved for mega-masers and quasars observed at 1.3 cm, respectively. Successful results have been obtained in all areas of its science program including active galactic nuclei, pulsars and scattering, galactic and extragalactic masers, gravitational redshift measurements. An overview of the mission as well as its science results will be presented.

Wednesday, January 29, 2020

Wednesday, January 29, 2020			
		Session: Technology Drivers	**Session Chair: Walter Brisken**
9:00 AM	9:40 AM	Technical Developments for Millimetron	A. Baryshev
9:40 AM	10:20 AM	Instrumentation Status for Space VLBI with the Event Horizon Telescope	K. Haworth
10:20 AM	10:50 AM	Break	
10:50 AM	11:10 AM	Recent Results in Millimeter (mmW) Performance of Mesh for Space Reflectors	S. Ortiz
11:10 AM	11:30 AM	Wideband Superconducting Parametric Amplifiers for Microwave and Millimeter Wavelengths	P. Day
11:30 AM	11:50 AM	APEX SEPIA345: a New Generation Receiver for EHT	V. Belitsky
11:50 AM	12:10 PM	Interferometric Imaging at Extreme Baselines and Spatial Frequencies	A. Zensus
12:10 PM	12:20 PM	Conference Photo	
12:20 PM	1:50 PM	Lunch (90 min)	
		Session: Technology Drivers con't	**Session Chair: Shep Doeleman**
1:50 PM	2:20 PM	Fundamental Physics of Moving Clock Time Synchronization in a Weak Gravitational Field	S. Wilkinson
2:20 PM	3:00 PM	Precise Satellite Orbit and Baseline Determination: Status and Outlook	P. Visser
3:00 PM	3:30 PM	Break	
3:30 PM	3:50 PM	Mission Optimization: From Science Goals to Orbit Selection	D. Palumbo
3:50 PM	4:10 PM	Incoherent Clocking and Potential Applicability to Space VLBI	B. Carlson
4:10 PM	5:10 PM	Discussion Topic: Common Requirements and Technology Developments?	
6:00 PM	9:00 PM	Conference Dinner	

Andrey Baryshev (Kapteyn Astronomical Institute/NOVA)

Topic: Technology Drivers, Synergies with other Instruments

Technical Developments for Millimetron Space Observatory

Millimetron Space Observatory (MSO) is a Space Earth Very Long Baseline Interferometer (VLBI) project to be realized by Russian Space Agency RosKosmos with the provisional launch date in the end of 2029. MSO is based on light deployable 10 m diameter telescope capable to operate up to 70 μm wavelength. Telescope is based on carbon fiber reinforced polymer composite material and has extremely low specific mass of 8.5 kg/m2. The receiver suite will include both heterodyne and direct detector instruments operating in 40 GHz .. 4.7 THz frequency range. MSO will be launched into a halo orbit around anti-Solar, Sun-Earth Lagrangian L2 point. In a later mission phase it is considered to use Moon gravitational assist maneuver to change the orbit to an eccentric elliptical type with an apogee of 320000 km and a perigee of 10000 km providing more opportunities for optimized u-v coverage in Space-Earth or Space-Space VLBI mode.

While MSO will operate in both single dish and VLBI modes, in this contribution we will focus on space VLBI operation of the observatory. To support the VLBI mode we are developing a set of an on board facilities which makes the VLBI operation possible. The VLBI front-end will consist of five dedicated observing bands covering from 33 GHz to 650 GHz with three high priority bands working in 84-373 GHz range. Cryogenically cooled receivers will be used to achieve the lowest possible noise temperature. For frequencies below 116 GHz HEMT amplifiers will be used which will maintain their operation for the post cryogenics phase of MSO. Cryogenic cooling of both instruments and the antenna will be done by a set of a closed cycled mechanical coolers with an expected cryogenic mission phase duration of more than 5 years.

The VLBI receiver band's beams will be quasi-optically combined to receive signal from one direction on the sky. MSO's VLBI receivers can be operated simultaneously supporting multi frequency synthesis (MFS) VLBI mode. Part of the receiver's IF 4-12 GHz band will be digitized and stored in an on board mass memory with a capacity of up to 100 TB. The stored astronomical signal will be then transmitter to an Earth station by means of high directional data link. The on-board time synchronization will be based on a highly stable space-qualified hydrogen mazer clocks.

In this contribution we will report the current status MSO mission as well as the development status of MSO antenna, VLBI front-end, and the other VLBI systems. We will demonstrate examples of MSO's static and dynamic imaging capabilities in operating together with ALMA and Event Horizon Telescope (EHT). We will also consider possible Space-Space VLBI using Millimetron concept.

Kari Haworth (Center for Astrophysics | Harvard & Smithsonian)

Alexander Raymond (Center for Astrophysics | Harvard & Smithsonian)

Topic: Technology Drivers

Instrumentation Status for Space VLBI with the Event Horizon Telescope

The Event Horizon Telescope is presently the highest-frequency VLBI experiment, operating at 230 GHz. The network of ground-based telescopes that has enabled that capability was built-up over several decades and involved deploying stable clocks, precision antennas, sensitive receivers, and wide bandwidth data recorders. What was challenging on the ground is far more so in space, where size, weight, and power can break a mission concept. In this talk we'll discuss the present stage of development for several technologies that will enable extending the EHT into space. Stable hydrogen maser frequency standards have flown in space, as have crystal oscillators with worse but still interesting performance. Submillimeter primary mirrors with modest apertures have flown, although at a much smaller diameter than what is currently used at most EHT ground stations. Cryocooled heterodyne receivers are space qualified. For some applications, a less sensitive receiver can be compensated by long integration times, but there are hard limits to integration time in space VLBI which we will briefly discuss. Wideband (up to 16 GHz) digitizers and data processing has not been demonstrated in space to our knowledge, but the development path is fairly straightforward. An additional need for the orbiting element is high-speed data transmission, and we will describe the present and near-term outlook for optical data links. Finally, we will present guidelines for the requirements on each of these technologies and explain the tradeoffs between them.

Sean Ortiz (L3Harris Technologies)

Topic: Technology Drivers

Recent Results in Millimeter (mmW) Performance of Mesh for Space Reflectors

L3Harris will report on recent advancements in knitted wire mesh for fixed and deployable reflectors at mmW frequencies. We have developed X-mesh to increase the reflectance of the mesh surface for fixed mesh reflectors at mmW frequencies due to increase in the transmissivity as the relative hole size increases in terms of wavelength. X-mesh increases the reflectance by adjoining two orthogonal mesh fabrics with 50 openings per inch (OPI). The resulting mesh has lower total transmissivity and thus an increase in reflectance. L3Harris will also present measured results in mmW, as well as mesh application to fixed and large deployable mesh reflectors.

Peter Day (Jet Propulsion Lab)

Topic: Technology Drivers

Wideband Superconducting Parametric Amplifiers for Microwave and Millimeter Wavelengths

We will discuss a relatively new type of superconducting amplifier, the kinetic inductance Traveling-wave Parametric Amplifier (TWPA), and its potential for use in millimeter-wave receivers. This type of parametric amplifier has demonstrated bandwidths exceeding an octave and recent results at microwave frequencies show that they operate at the so-called quantum limit of sensitivity. The kinetic inductance TWPA is based on the nonlinear kinetic inductance of an NbTiN transmission line, which allows for the transfer of power from a strong pump tone to a weaker signal via three- or four-wave mixing processes. The concept may be applied up to frequencies approaching the gap frequency of the superconductor, in this case around 1.4 THz, potentially allowing TWPAs to serve as quantum limited front end amplifier throughout the millimeter-wave band. We will describe the design of a W-band TWPA and the first observation of gain in this device at 90 GHz. Another, perhaps nearer term application would be as an IF amplifier following a SIS mixer, which could allow the system noise temperature of a receiver to more closely approach the quantum limit.

Victor Belitsky (GARD, Chalmers University of Technology)

Topic: Technology Drivers, Synergies with other Instruments

APEX SEPIA345: a New Generation Receiver for EHT

We report on the design and performance of the new receiver 275-370 GHz to be installed at Atacama Pathfinder Experiment (APEX) telescope. This new receiver is made as an ALMA cartridge and will be part of the Swedish ESO PI Instrument (SEPIA). At the workshop, we present details of the receiver and its components' design, the receiver performance and our plans on the integration the receiver into the SEPIA. This receiver will be used as APEX next generation EHT instrument.

Anton Zensus (Max-Planck-Institut für Radioastronomie, Bonn, Germany)

Eduardo Ros (Max-Planck-Institut für Radioastronomie, Bonn, Germany)
Anton Zensus (Max-Planck-Institut für Radioastronomie, Bonn, Germany)

Topic: Science Goals, New Mission Concepts

Interferometric Imaging at Extreme Baselines and Spatial Frequencies

The task of increasing the angular resolution of interferometric imaging drives to extremes both the baseline length and the spatial frequency of the measurements. Experience from the previous space VLBI missions has shown that even a modest increase of the baseline length by a factor of three achieved by VSOP taps the information inaccessible by simply extrapolating the models obtained from smaller spatial frequencies. Observations with RadioAstron reaching the current world records in baseline length and spatial frequency have revealed the full complexity of the task of achieving a successful imaging with such an extreme interferometric setup. The issues there range from accounting for the structural phase during the fringe fit on extreme baselines to dealing reliably with degeneration of the synthesized beam and missing spatial frequencies which sometimes lead to almost an order of magnitude increase of noise on intermediate-to-finest angular scales in the image. The next generation space VLBI missions proposed for imaging in the millimeter domain will have to deal with similar issues, compounded further by the fast variability of key target sources. We will present here an overview of the experience gained from the imaging programs carried out with VSOP and RadioAstron and discuss their implications to the imaging and information extraction approaches for the upcoming space VLBI missions.

Steven Wilkinson (Raytheon Space and Airborne Systems)

Topic: Technology Drivers

Fundamental Physics of Moving Clock Time Synchronization in a Weak Gravitational Field

This talk will present the fundamental physics of near earth dynamic clocks and time synchronization. We begin by establishing basic clock behavior and reviewing established synchronization approaches between two stationary clocks in separated ground based laboratories. A discussion of different clock technologies that are in the literature will include comparisons of short term and long term stability including a relationship between stability and volume. Once clocks start moving in a gravitational field we must use General Relativity to understand the behavior of time as compared to other clocks that are either stationary or moving. We start with a one spatial and one time dimension to show how motion causes clocks to run at different rates and synchronization asymmetries that must be corrected. We then discuss the transformation of proper time to coordinate time just as done in GPS clocks. Then we'll conclude by investigating the fundamentals of 4-dimensional dynamic clock synchronization of coordinate time.

Pieter Visser (Delft University of Technology)

Leonid Gurvits (JIVE)

Topic: Technology Drivers

Precise Satellite Orbit and Baseline Determination: Status and Outlook

Space-borne VLBI requires very precise determination of the baseline vector between the antennas of contributing satellites, down to below the cm and even mm level depending on the observing frequency. Many earth-orbiting satellites are nowadays equipped with high-quality Global Positioning System (GPS) receivers that typically allow absolute positioning with cm-level precision. For low earth formation flying satellites with baselines up to 250 km, sub-mm precision level with GPS has been demonstrated for the inter-satellite range for 10 s time intervals. For Space-borne VLBI, satellites are anticipated to fly in Medium-Earth Orbits (MEO) at altitudes around ~14 000 km and continuously varying inter-satellite distances up to more than 10 000 km, which poses challenges to very high, sub-cm or sub-mm precision baseline determination. Current and future developments include the development of space-borne multi-GNSS (Global Navigation Satellite System) receivers, where not only GPS satellites but as a minimum also satellites of the European Galileo system can be tracked. It is anticipated that this will lead to enhanced precise satellite orbit and baseline determination capabilities and precisions. Moreover, the range and range-rate between Space-borne VLBI MEO satellites can be measured very precisely by establishing Inter-Satellite Links (ISLs).

Daniel Palumbo (Center for Astrophysics | Harvard & Smithsonian)

Topic: Technology Drivers

Mission Optimization: From Science Goals to Orbit Selection

Different science goals favor a variety of very-long baseline interferometry (VLBI) array geometries depending on the precise Fourier sampling needs of particular measurements. We present an expanded toolkit for the generation of synthetic VLBI data from arrays including both ground and space dishes. We use these tools in example cases of optimizing dish placement in expanded Event Horizon Telescope arrays for multiple science goals, including imaging rapidly evolving compact structure at the galactic center and imaging diffuse jet structure near the supermassive black hole in Messier 87. We find that example reconstructions broadly corroborate the estimated improvements between different hypothetical arrays. Array optimization approaches for non-imaging science goals are also explored.

Brent Carlson (National Research Council of Canada)

Topic: Technology Drivers, New Mission Concepts

Incoherent Clocking and Potential Applicability to Space VLBI

"Incoherent clocking" (IC) is currently being researched as a new method to provide clock and timing for radio telescope arrays. In this method, each array element operates using its own independent local oscillator (LO) for down-conversion and digitization. The digitized data is then sent to a central location using commercial off-the-shelf (COTS) digital fiber optic modules and cables, where each element's LO frequency vs time behavior is extracted from the digital link receiver and precisely and accurately measured relative to the central common reference, using all digital methods in COTS devices (e.g. FPGAs). With this information, the data is digitally re-sampled/interpolated to the common reference frequency before correlation. It is clear that the fiber link connecting each array element to the central location confuses the frequency vs time measurement; round-trip measured phase and post-measurement digital filtering are used to remove these effects, yielding the desired behavior of the elements' LOs. It is conceivable that this method, using a wireless two-way link between the satellite and the ground, could be used to effectively down-convert and digitize the astronomical signal received by the satellite with clocks locked to a (tracking station) LO reference. If successful, there would be no need to deploy a space-qualified hydrogen maser on the satellite, or use the pre-Doppler-shifted LO up-conversion and transmission method as in VSOP. All that is needed is a satellite LO that is stable enough in frequency on a timescale to allow separation of LO behavior from link behavior, including differential atmospheric turbulence effects, in the measurement. This talk will discuss the incoherent clocking concept, some current research results and upcoming plans, and notional applicability to an orbiting Space VLBI satellite.

Thursday, January 30, 2020

Thursday, January 30, 2020			
		Session: Technology Drivers and Mission Concepts	**Session Chair: Joseph Lazio**
9:00 AM	9:40 AM	The Future of ALMA	I. Cleeves
9:40 AM	10:00 AM	Progress in the Event Horizon Imager Mission Concept	M. Martin-Neira
10:00 AM	10:20 AM	MicroArc Second Astrometry with Multi-Beam Space VLBI	M. Eubanks
10:20 AM	10:50 AM	Break	
10:50 AM	11:10 AM	The U.S. Space VLBI Program	D. Murphy
11:10 AM	11:30 AM	Expanding the Event Horizon Telescope into a MEO/GEO-sized Imaging Array	K. Akiyama
11:30 AM	11:50 AM	Two Options for Space VLBI Telescope Orbit: LEO and GEO	Y. Asaki
11:50 AM	12:10 PM	A Proposal of Space Terahertz Intensity Interferometry	H. Matsuo
12:10 PM	1:40 PM	Lunch (90 min)	
		Session: Technology Drivers and Mission Concepts, con't	**Session Chair: Tony Beasley**
1:40 PM	2:20 PM	Space VLBI in the ngVLA Era	E. Murphy
2:20 PM	3:20 PM	Discussion Topic: Mission Architecture - One Big Space Antenna vs. Many Small Antennas?	
3:20 PM	3:30 PM	Concluding Remarks	

Ilse Cleeves (University of Virginia)

Tony Beasley (NRAO)

Topic: Synergies with other Instruments

The Future of ALMA

This talk will present the fundamental physics of near earth dynamic clocks and time synchronization. We begin by establishing basic clock behavior and reviewing established synchronization approaches between two stationary clocks in separated ground based laboratories. A discussion of different clock technologies that are in the literature will include comparisons of short term and long term stability including a relationship between stability and volume. Once clocks start moving in a gravitational field we must use General Relativity to understand the behavior of time as compared to other clocks that are either stationary or moving. We start with a one spatial and one time dimension to show how motion causes clocks to run at different rates and synchronization asymmetries that must be corrected. We then discuss the transformation of proper time to coordinate time just as done in GPS clocks. Then we'll conclude by investigating the fundamentals of 4-dimensional dynamic clock synchronization of coordinate time.

Manuel Martin-Neira (European Space Agency)

Volodymyr Kudriashov (Radboud Universiteit Nijmegen)
María Manzano Jurado (GMV)
Aron Kisdi (GMV)
Jaime Fernández Sánchez (GMV)

Topic: New Mission Concepts

Progress in the Event Horizon Imager Mission Concept

The Event Horizon Imager (EHI) mission concept consists of a constellation of two satellites in Medium Earth Orbit flying well within the GNSS orbital shell and performing interferometry in three channels (around 40, 240 and 600 GHz) suited to obtain a sharp image of the event horizon of a black hole like Sagittarius A or M87. EHI features single dish antennas of the order of 4.5 m, wide bandwidth inter-satellite links, on-board pre-correlation and oscillator signal swapping and mixing to achieve the required level of coherence.

Two critical aspects of EHI are the oscillator signal swapping and mixing and the relative positioning. A demonstrator of the former is being built at the radio-frequency laboratory of ESTEC. The subsystems needed for the oscillator concept demonstrator are being procured and will be assembled in a step-wise approach until completing the whole set-up, in order to measure the coherence between the oscillator outputs emulating those on each of the two satellites. On the other hand, the relative positioning is being analyzed in detail at two levels: real time and postprocessing. Both use as main navigation sources GNSS relative positioning and ranging through the optical link. In postprocessing, it is intended to use the radiation from the black hole itself, helping with the lower channels the search of fringes of the highest one.

This presentation will briefly introduce the EHI mission concept and will focus on the latest results obtained in the areas of oscillator coherence and relative positioning.

Thomas Eubanks (Space Initiatives Inc)

Topic: Technology Drivers

MicroArc Second Astrometry with Multi-Beam Space VLBI

The use of Very Long Baseline Interferometry (VLBI) using space components have shown that the power of this technique can be extended to baselines longer than the diameter of the Earth. In particular, the RadioAstron mission, with a 10 meter space radio telescope used in conjunction with terrestrial VLBI arrays, found useful VLBI fringes at 1.7, 4.8, and 22 GHz with projected baselines up to 240,000 km, or a substantial fraction of a lunar distance. This produced imaging resolution at the micro arc second level, and showed that natural radio sources can exhibit brightness temperatures > 1013 K. This work clearly needs to be continued and extended with larger space radio telescope at even higher frequencies.

However, neither the HALCA (VSOP) or RadioAstron missions were capable of producing global astrometric results using the long space to Earth baselines, due to the inability of large telescopes in free space to rapidly slew from one source to another. That limitation is likely to continue for space radio interferometry at centimeter and millimeter wavelengths for the foreseeable future (a Very Large Baseline Array on the Moon is clearly still a long way off).

The Japanese VERA (VLBI Exploration of Radio Astrometry) project is an array of multi-beam VLBI antennas used mostly at 22 and 48 GHz for differential for phase referencing extragalactic sources and astronomical water and silicon oxide masers. The two VERA beams can be varied up to a separation of 2.2 degrees, which allows for a reasonable probability of finding a phase reference source near the desired target. Because the two beams are close together in the sky, and the differential VLBI is done with pairs of sources with the same clock, very close paths through the atmosphere, and similar instrumental and antenna delays, VERA is capable of highly accurate differential astrometry, with an accuracy goal of ~ 10 micro arc seconds.

A multibeam space telescope or telescopes could be used to construct a space-Earth or space-space Celestial Reference Frame (CRS), providing a substantial increase in both global astrometric accuracy and differential phase VLBI. A major science goal for an accurate space astrometric reference frame would be to monitor gravitational lensing events astrometrically, as well as to improve the CRS to better than the accuracy provided by the Gaia spacecraft.

This presentation will focus on optimizing a multibeam system for the construction of a global CRS with an antenna or antennas orbiting in cislunar space.

David Murphy (Jet Propulsion Laboratory)

Topic: Synergies with other Instruments

Lessons Learned from U.S. Space VLBI Project

The role of the NASA-funded U.S. Space VLBI Project to support both the VSOP and RadioAstron missions is described as well as lessons learned from this activity with the consequent hope that better support can be provided for future Space VLBI missions.

Kazunori Akiyama (NRAO / MIT Haystack Observatory)

Vincent Fish (MIT Haystack Observatory)

Topic: Science Goals, Technology Drivers, New Mission Concepts

Expanding the Event Horizon Telescope into a MEO/GEO-sized Imaging Array

The current Event Horizon Telescope achieves an angular resolution of ~20 μas, capable of resolving horizon-scale emission in M87* and Sgr A*. At the observing wavelength of 1.3 mm, these are the only two sources for which a ground-based array can resolve the emission from the photon ring. A potential direction for next-generation EHT developments will be to extend the EHT into space, expanding the number of available targets. In this talk, we will present systematic studies of the orbits required for imaging multiple targets at an angular resolution down to 2 μas. We analyze the orbital-plane characteristics of such an array and test performance with metrics such as uv-filling and resultant beam circularity. We find that at least two satellites are needed to image targets down to 3 μas and that one or two more additional satellites provide a stable imaging performance across multiple targets. Many sources of interest fall within these scales and would be optimally observed with such an array, enabling us to explore and monitor the horizon-scale emission of multiple nearby supermassive black holes.

Yoshiharu Asaki (National Astronomical Observatory of Japan)

Seiji Kameno (NAOJ/JAO)

Topic: New Mission Concepts

Two Options for Space VLBI Telescope Orbit: LEO and GEO

Millimeter-wave space VLBI with high sensitivity terrestrial telescopes like ALMA is an attractive idea for future radio astronomy observations. We present mm-wave space VLBI concept from u-v coverage point of view by considering two orbit options: one is low earth orbit (LEO), and the other is geo-stationary earth orbit (GEO). The former in the sun-synchronous orbit has a great merit to form well-filled u-v coverage especially for objects at around the celestial equator. However, a VLBI observation data transmission from the satellite to the ground is not so effective using a few tracking stations that the real-time observation data link is hardly achieved. In the case of GEO, on the other hand, the space telescope is almost always visible from a specific sight on the earth whereas there are remarkable gaps in the u-v coverage. We also present some tips of on-board subsystem required for a few cm level precise orbit determination for a space VLBI telescope.

Hiroshi Matsuo (National Astronomical Observatory of Japan)

Topic: New Mission Concepts

A Proposal of Space Terahertz Intensity Interferometry

Intensity Interferometry, known by the names Hanbury-Brown and Twiss, can be applied to long baseline space interferometry using high sensitivity direct detectors. By using fast direct detectors, complex visibility can be measured in terms of delay time obtained using intensity fluctuation caused by photon bunches, enabling aperture synthesis imaging. Modern superconducting detectors can be used as the fast and sensitive detectors in terahertz frequencies. Typical photon rate from bright compact sources (~1 Jy source) is estimated to be approximately 100 Mphoton/s. Using detectors with NEP less than 10(-17) W/Hz(0.5) with nanosecond time resolution, photon counting will be realized. The terahertz intensity interferometry could be based on such photon counting detectors.

System requirements to terahertz intensity interferometry can be like VLBI, since correlation analysis can be made after detector signals are collected on each telescope. But, requirements to phase stability is different from heterodyne interferometry. Since coherent time of intensity fluctuation is inverse of radiation bandwidth, intensity correlation is not much affected by phase fluctuation and stable correlation signal can be obtained in terahertz frequencies. On the other hand, delay time or phase calibration need longer integration than heterodyne interferometry when sensitivity is the same. But, high sensitivity of direct detector, say noise temperature of 10 mK, sensitivity can be improved appreciably, enabling delay time (phase) calibration in terahertz frequencies.

Image quality of intensity interferometry can be another issue to be studied. Since correlation drops faster as a function of source structures due to second order correlations, requirements to baseline configuration is different from heterodyne interferometry. Requirement to the large dynamic range measurements of intensity interferometry should be studied further.

Potential merit of intensity interferometry is its high sensitivity in terahertz frequencies using cryogenic telescopes in space, like Origin Space Telescope (OST). Combining VLBI technologies, such as accurate attitude measurements, time reference and fast data recorders, with cryogenic telescopes in space with fast photon counting detectors, it will be possible to realize Space Terahertz Intensity Interferometry (STII).
It is of great interest to image active galactic nuclei with high sensitivity using atomic lines in terahertz frequencies to resolve broadline regions and accretion discs. Imaging exoplanet forming sites are another topic of interest for STII, such as imaging ice feature in protoplanetary disks or even imaging exoplanets themselves.

Eric Murphy (NRAO)

Topic: Synergies with other Instruments

Space VLBI in the ngVLA Era

With an expected timeline of ~20-25 yr before future Space VLBI missions take flight, they will likely operate concurrently with a next-generation cm-to-mm interferometer whose capabilities will vastly exceed the VLA and VLBA, such as the next-generation VLA (ngVLA). Building on the superb cm observing conditions and existing infrastructure of the VLA site, the current vision of the ngVLA is an interferometric array with more than 10 times the sensitivity and spatial resolution of the current VLA and ALMA, that will operate at frequencies spanning ~1.2. – 116 GHz. The ngVLA will greatly expand current U.S. VLBI capabilities by both replacing existing VLBI antennas/infrastructure with ngVLA technology and adding additional stations on 1000 km baselines to bridge the gap between baselines across the U.S. Southwest and existing VLBA baselines. The ngVLA will be optimized for observations at wavelengths between the exquisite performance of ALMA at submm wavelengths, and the future SKA-1 at decimeter to meter wavelengths, thus lending itself to be highly complementary with these facilities as a final piece to a suite of transformational radio capabilities. Within this global suite of radio instruments, the ngVLA will open a new window on the universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcecond resolution, as well as deliver unprecedented broad band continuum polarimetric imaging of non-thermal processes (e.g., the formation and evolution of stellar and supermassive blackholes in the era of multi-messenger astronomy) that can be further leveraged via Space VLBI missions. The next generation Very Large Array is a design and development project of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.